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(54) **DIFFERENTIAL MIMO TRANSCEIVER**

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(73) Assignee: **Wisconsin Alumni Research Foundation**, Madison, WI (US)

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This patent is subject to a terminal disclaimer.

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Related U.S. Application Data

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(51) **Int. Cl.**

H04L 1/06	(2006.01)
H04L 25/03	(2006.01)
H04B 7/06	(2006.01)
H04B 7/0413	(2017.01)

(52) **U.S. Cl.**

CPC ***H04L 1/0618*** (2013.01); ***H04L 25/03*** (2013.01); *H04B 7/0413* (2013.01); *H04B 7/0617* (2013.01); *H04B 7/0626* (2013.01); *H04B 7/0697* (2013.01)

(58) **Field of Classification Search**

CPC ... H04B 7/0617; H04B 7/0626; H04B 7/0697
See application file for complete search history.

(56) **References Cited**

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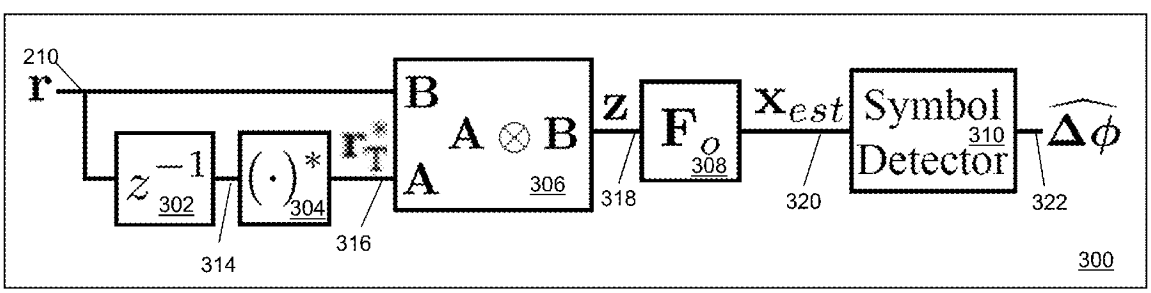
(74) *Attorney, Agent, or Firm* — Bell & Manning, LLC

(57) **ABSTRACT**

A receiver detects a plurality of information symbols. A first signal and a second signal are received from a first transmitted signal and a second transmitted signal, respectively, transmitted by a first plurality of antennas and received by a second plurality of antennas connected to the receiver. The second signal is received after the first signal. The receiver spatially filters the first signal using a spatial filter matrix. The receiver computes a conjugate of the first filtered signal to define a conjugate first signal, and spatially filters a second signal using the spatial filter matrix. The receiver computes a Hadamard product of the first filtered signal and the conjugate first signal to define a differential measurement signal. The receiver detects the plurality of information symbols from the differential measurement signal.

20 Claims, 15 Drawing Sheets



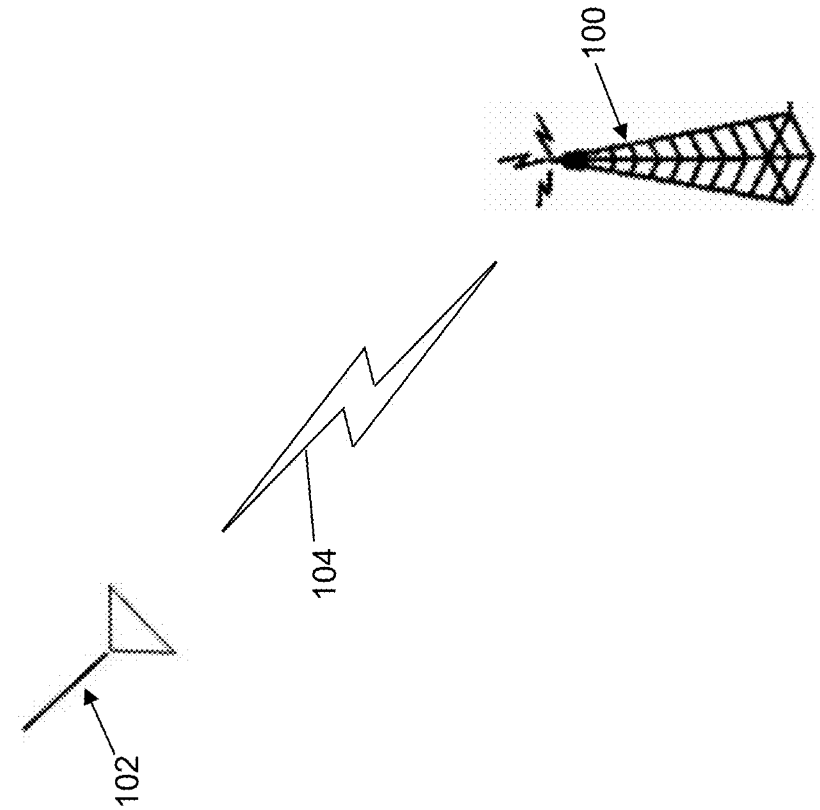


Fig. 1

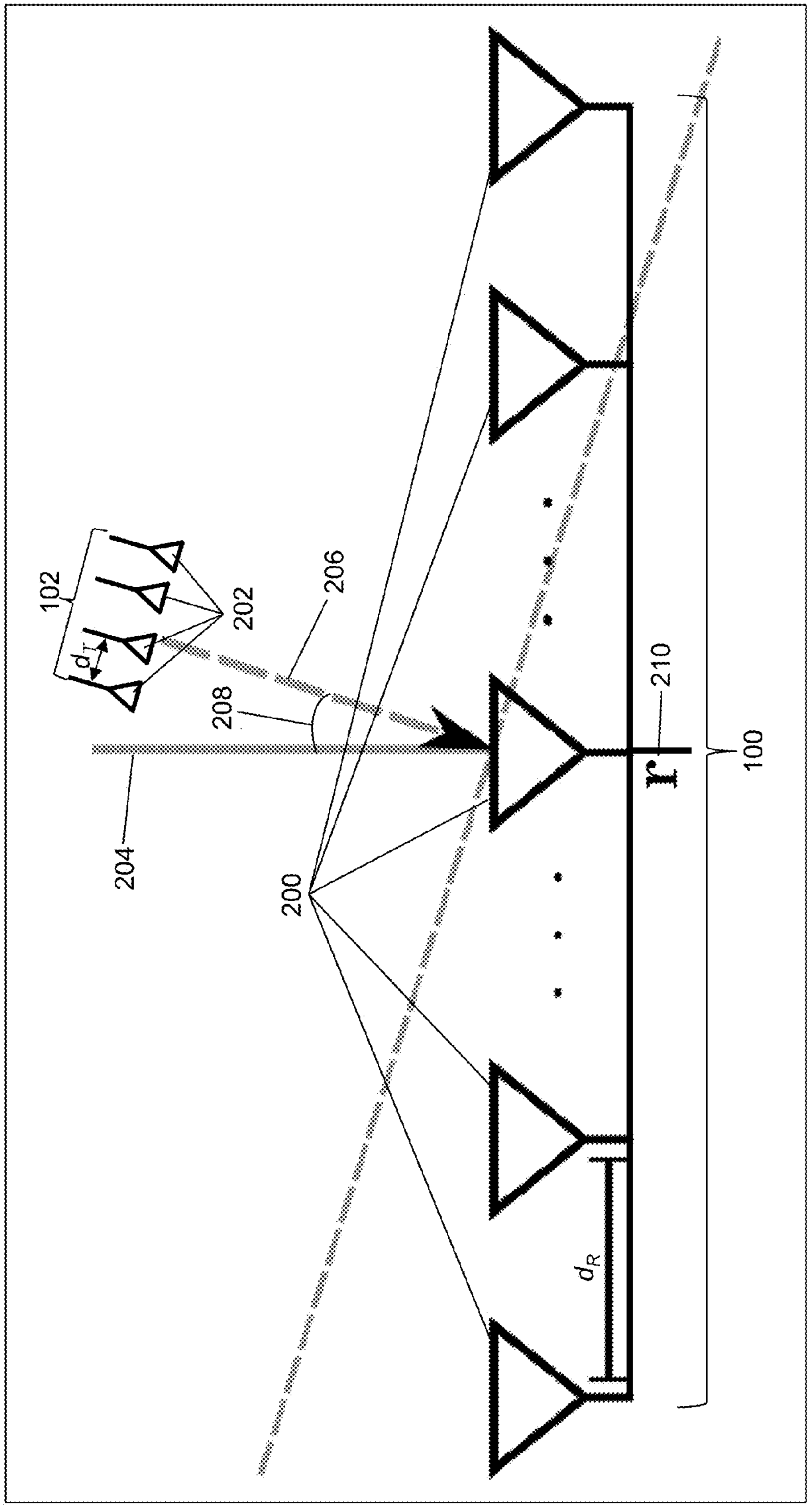
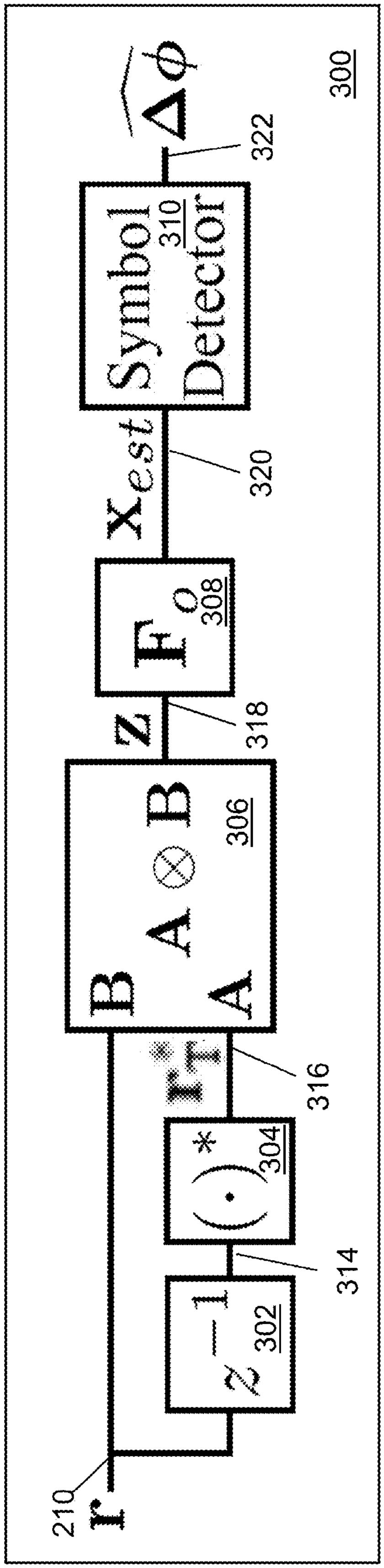


Fig. 2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210
302
314
304
316
306
318
308
320
Symbol
310
Detector
322

Fig. 3

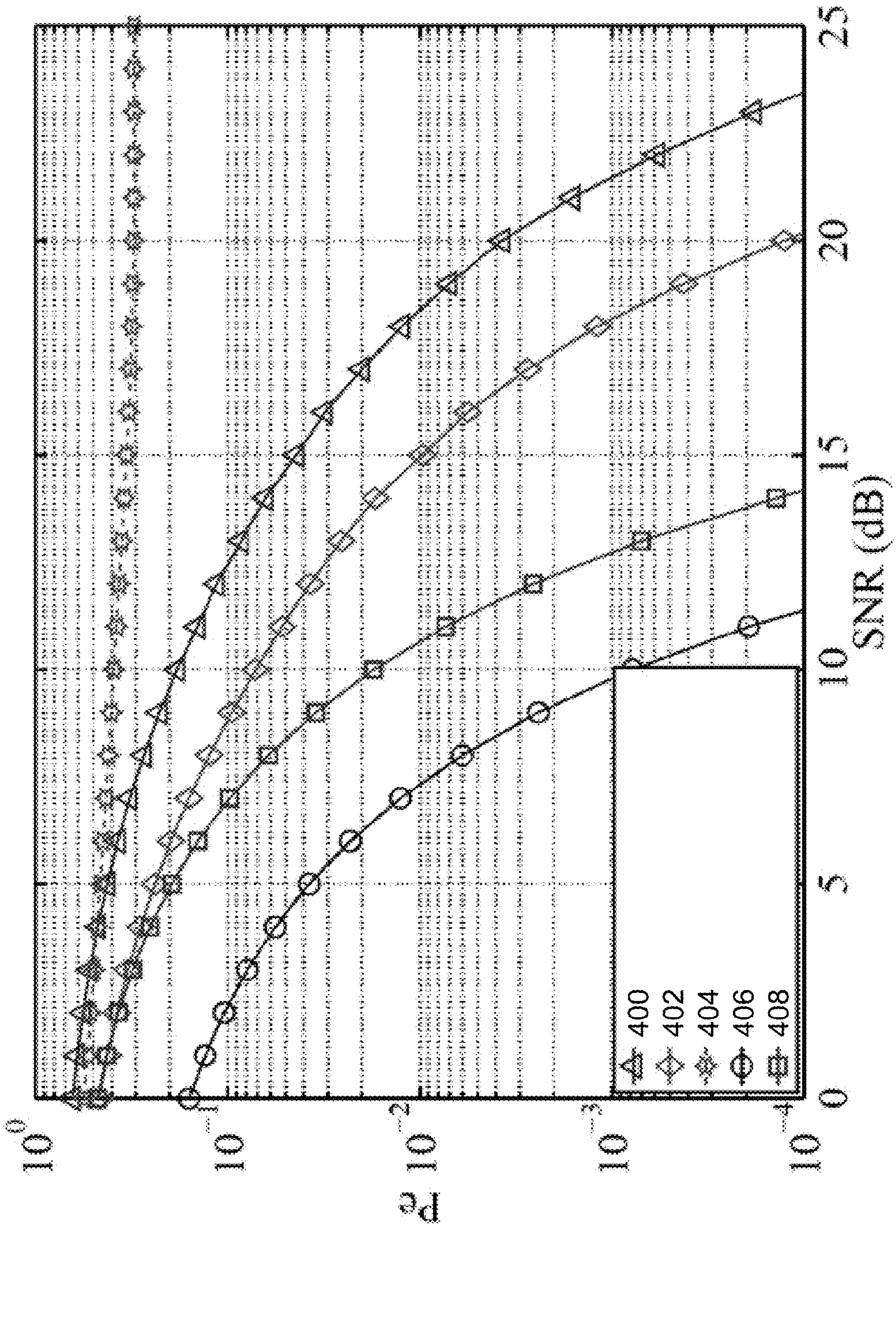


Fig. 4a

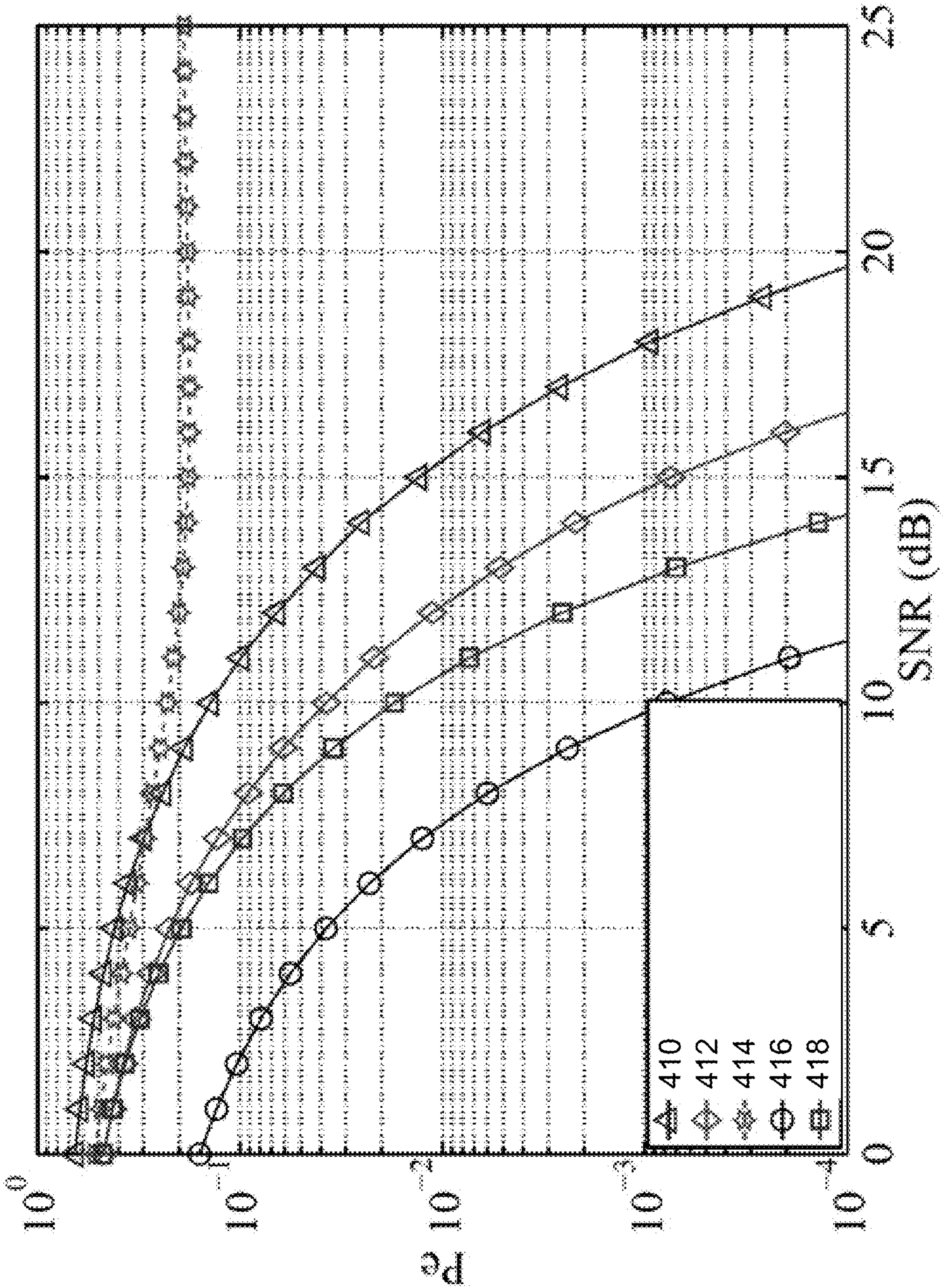


Fig. 4b

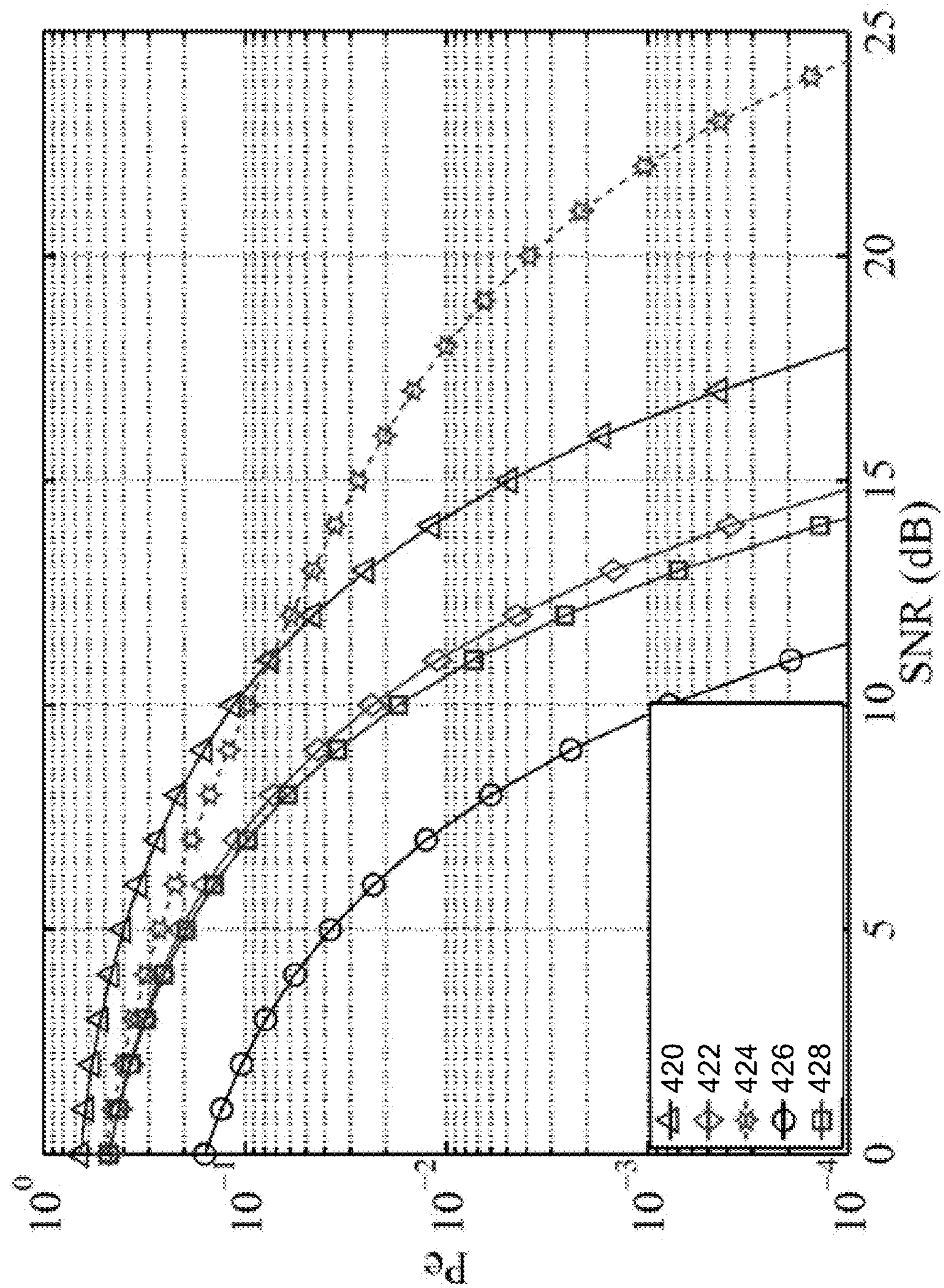


Fig. 4c

Fig. 5

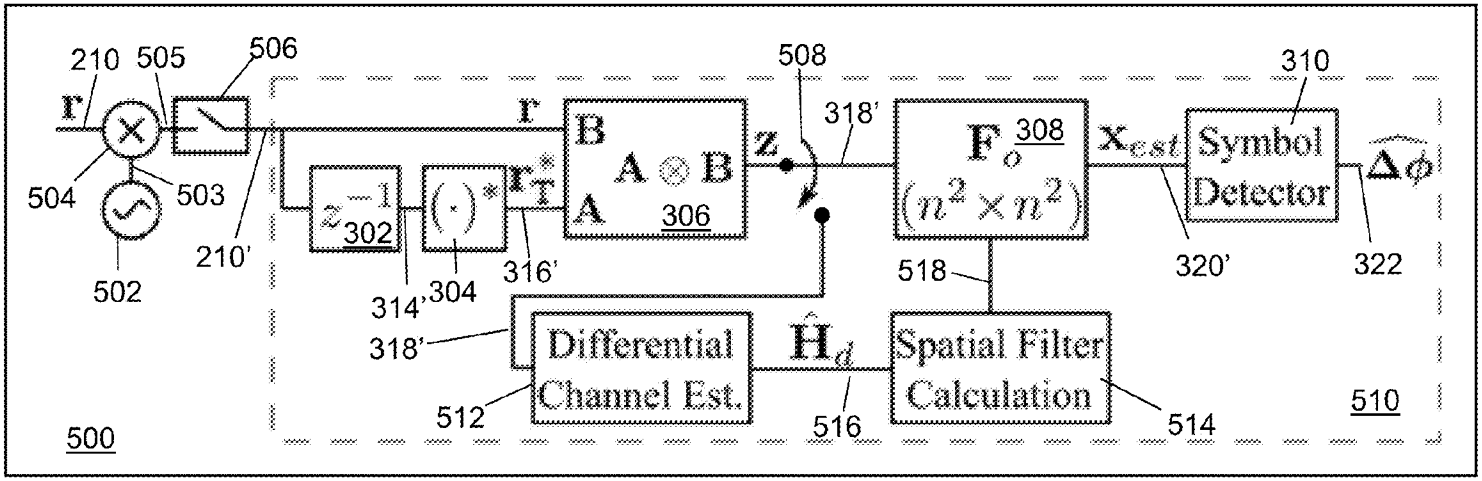

210
505
506
r
504
503
502
210'
r
z⁻¹
302
314'
(·)*
304
316'
r*T
B
A ⊗ B
A
306
z
508
318'
Fo
308
(n² × n²)
xest
Symbol Detector
310
Δφ
320'
322
518
318'
Differential Channel Est.
512
Ĥd
516
Spatial Filter Calculation
514
510
500

Fig. 6

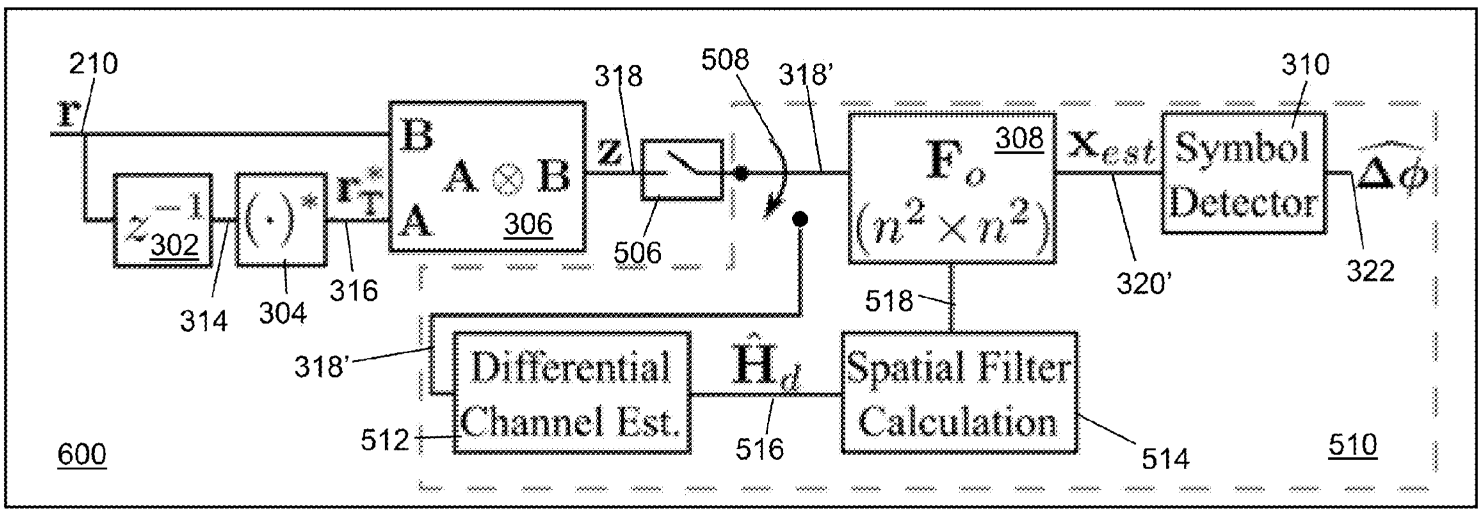
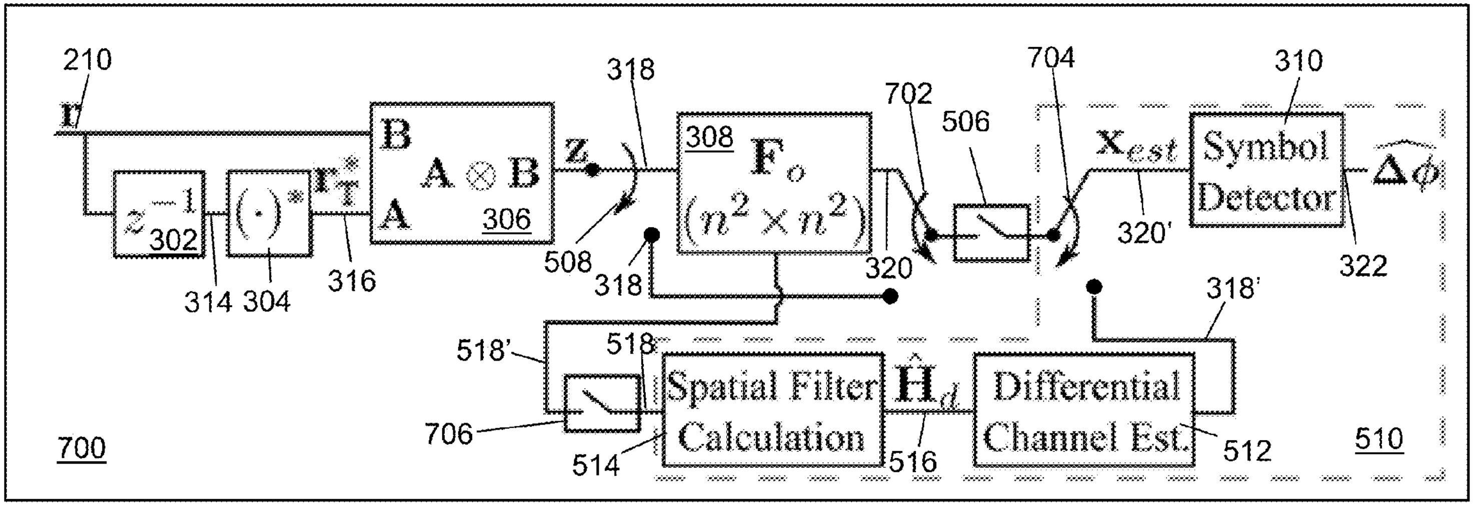

210
r
z⁻¹
302
314
(·)*
304
316
r*T
B
A ⊗ B
A
306
z
318
506
508
318'
Fo
308
(n² × n²)
xest
Symbol Detector
310
Δφ
320'
322
518
318'
Differential Channel Est.
512
Ĥd
516
Spatial Filter Calculation
514
510
600

Fig. 7


210
r
z^{-1}
302
$(\cdot)^*$
304
314
316
$\mathbf{r}_T^*$
B
A
$\mathbf{A} \otimes \mathbf{B}$
306
z
318
508
308
$\mathbf{F}_o$
$(n^2 \times n^2)$
320
702
506
704
$\mathbf{x}_{est}$
320'
310
Symbol Detector
$\widehat{\Delta\phi}$
322
318'
518'
518
706
514
Spatial Filter Calculation
$\hat{\mathbf{H}}_d$
516
Differential Channel Est.
512
510
700

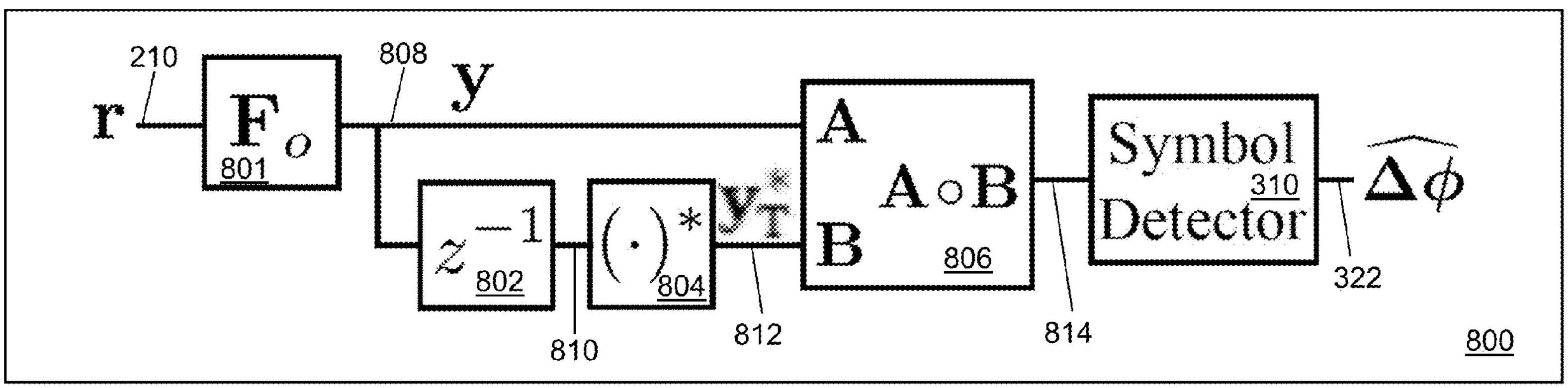

r
210
$\mathbf{F}_o$
801
808
y
z^{-1}
802
$(\cdot)^*$
804
$\mathbf{y}_T^*$
810
812
A
B
$\mathbf{A} \circ \mathbf{B}$
806
814
Symbol Detector
310
$\widehat{\Delta\phi}$
322
800

Fig. 8

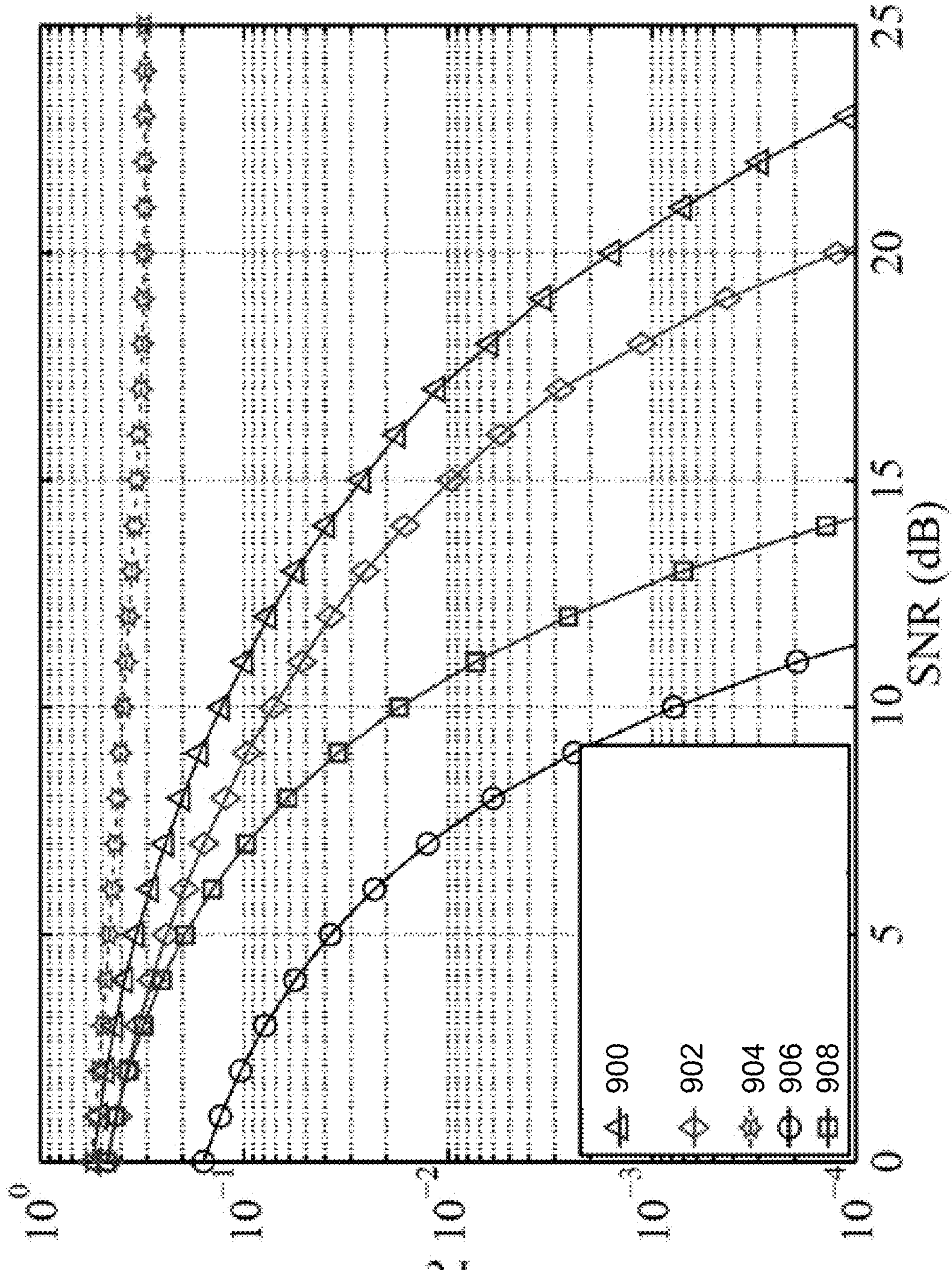


Fig. 9a

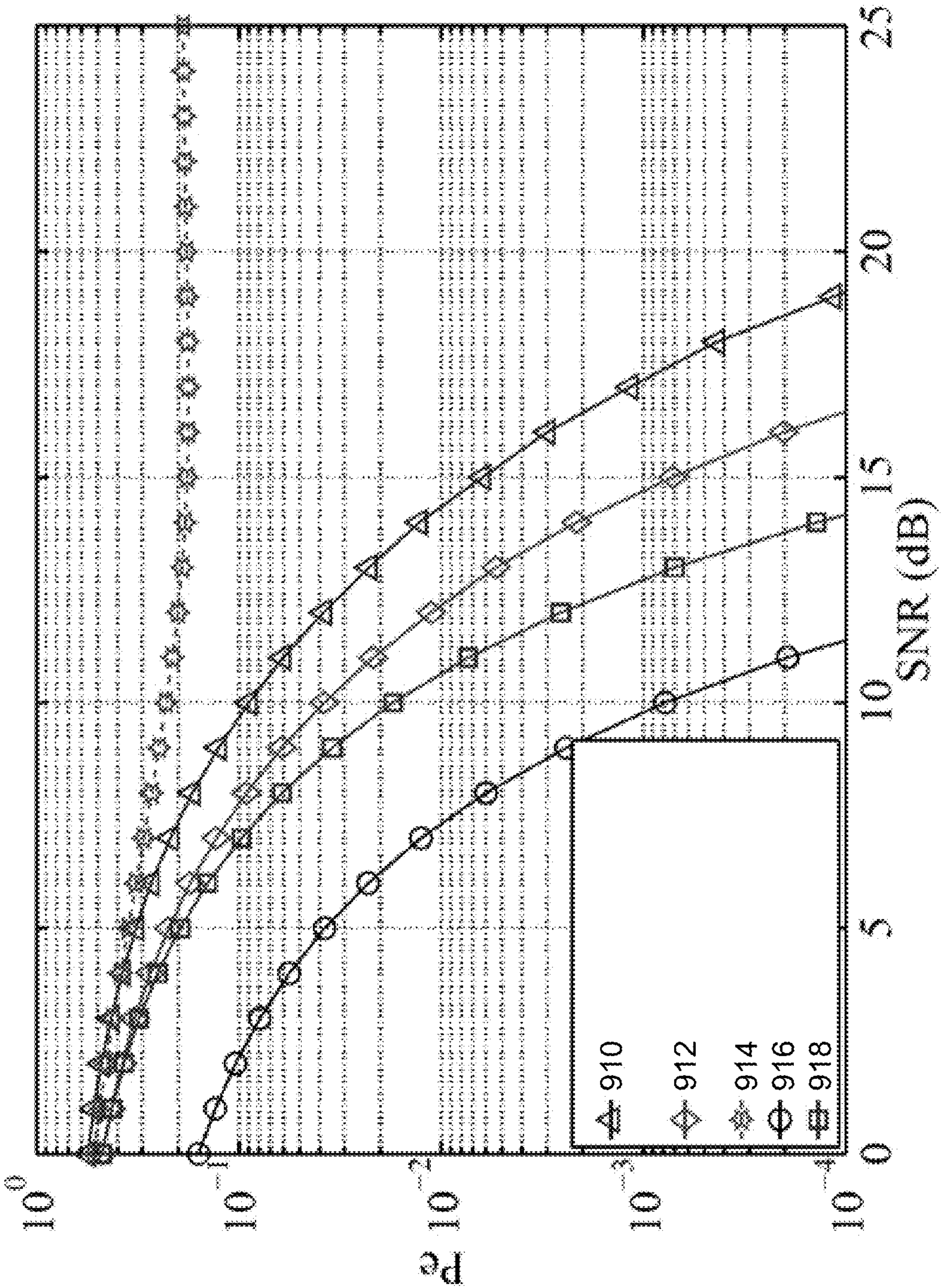


Fig. 9b

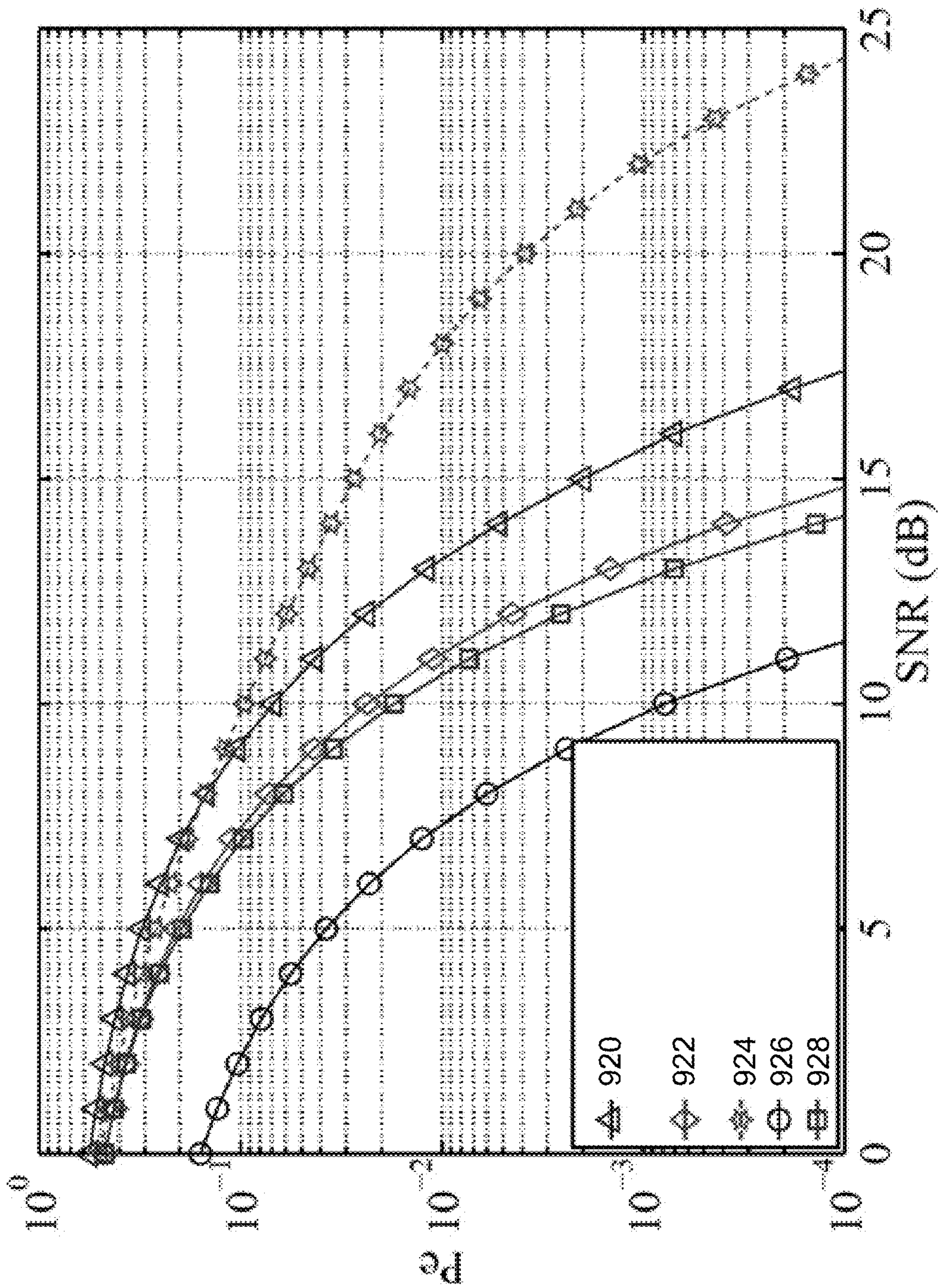


Fig. 9c

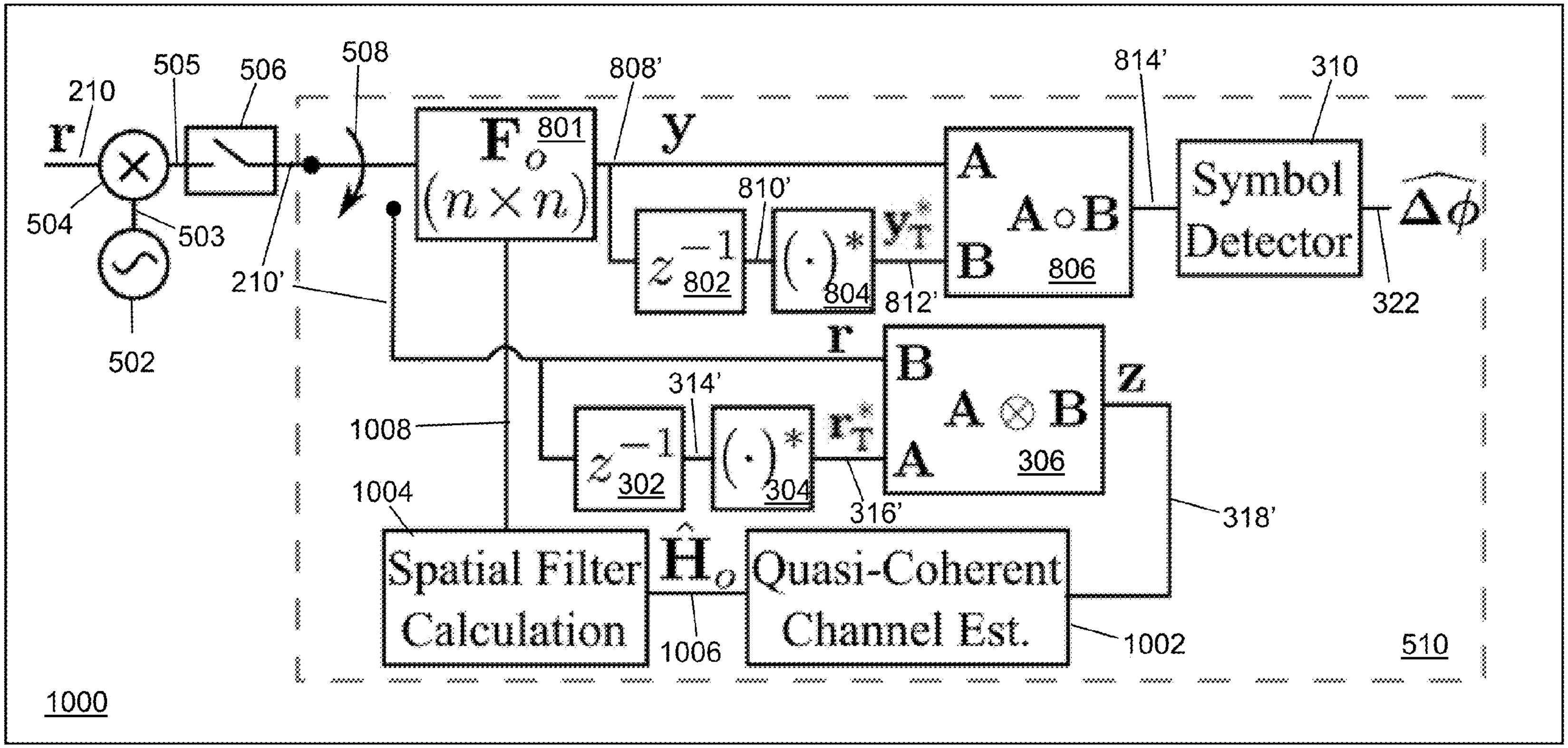
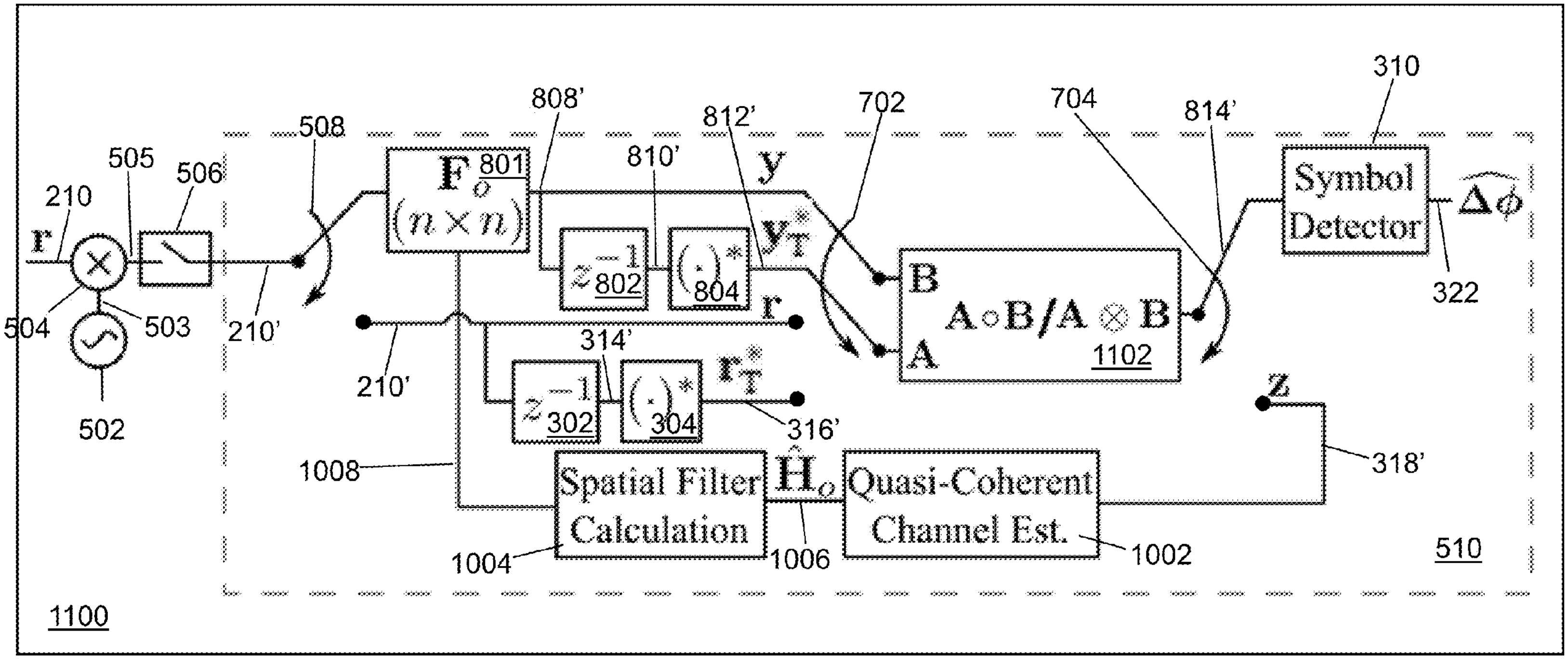
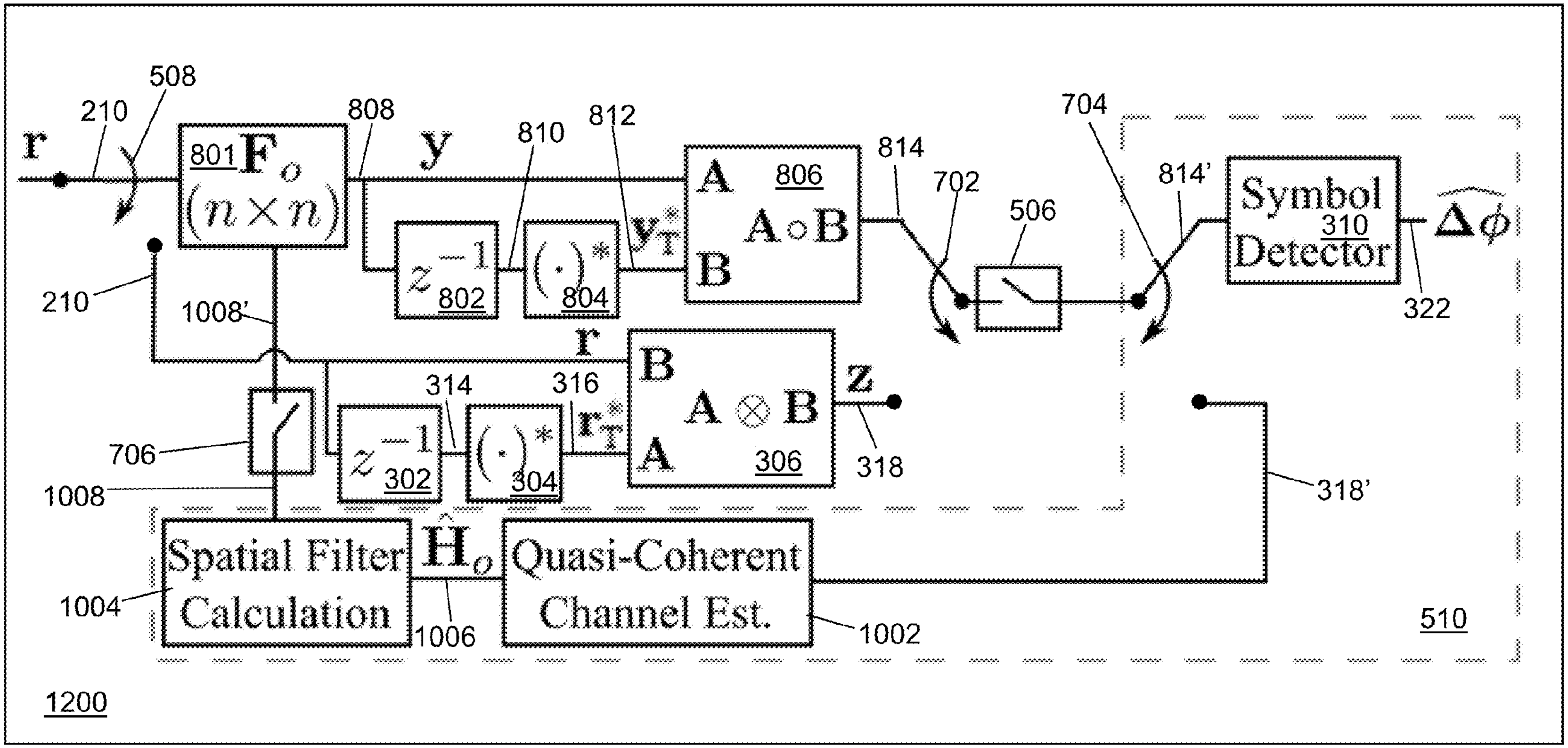

r
210
505
506
508
808'
814'
310
504
503
502
210'
801
802
810'
804
812'
806
Symbol Detector
322
r
z
314'
302
304
306
316'
318'
1008
1004
Spatial Filter Calculation
1006
Quasi-Coherent Channel Est.
1002
510
1000

Fig. 10



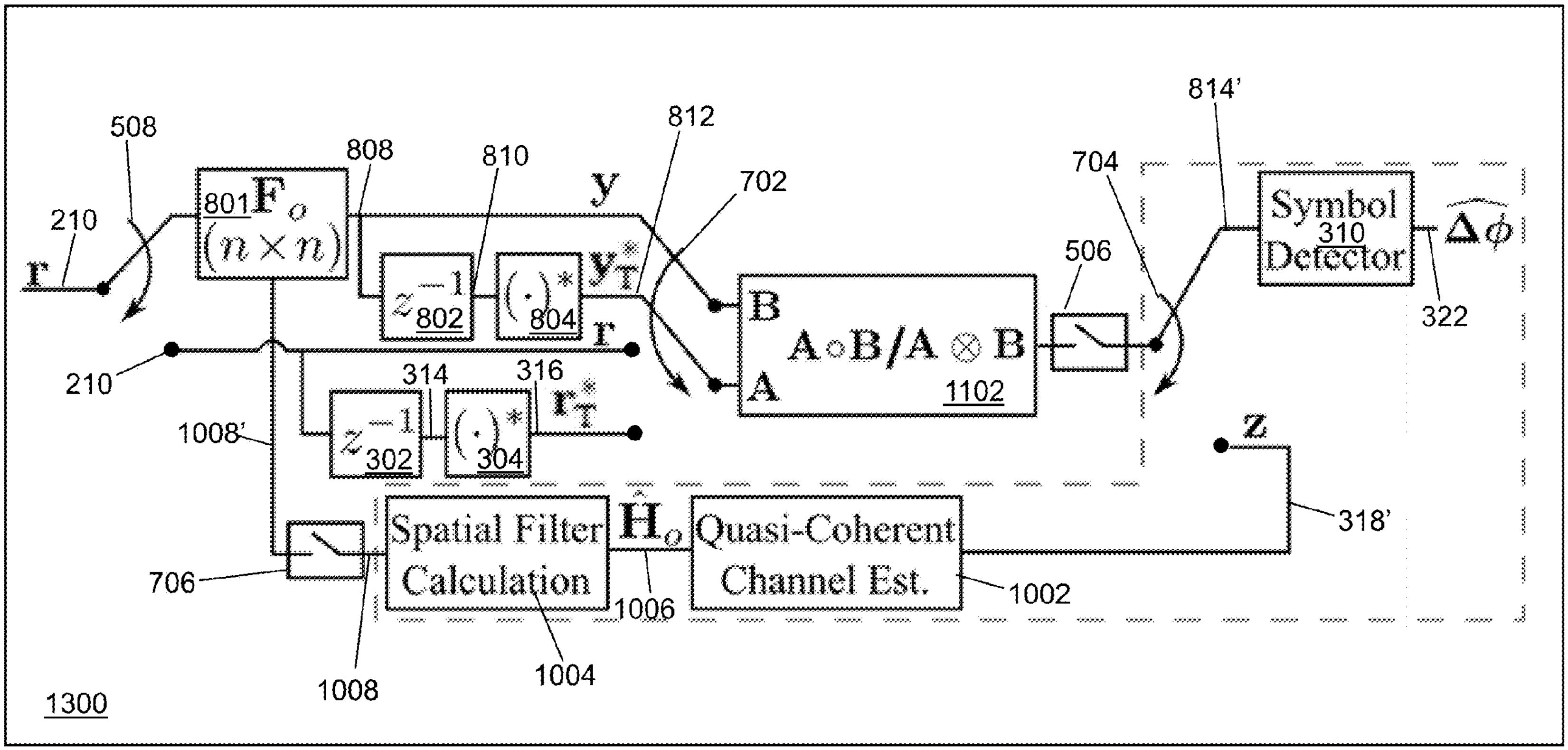
r
210
505
506
508
504
503
502
210'
801
(n × n)
808'
810'
812'
y
802
804
r
210'
314'
302
304
316'
1008
Spatial Filter Calculation
1004
1006
Quasi-Coherent Channel Est.
1002
702
704
814'
B
A
A∘B/A ⊗ B
1102
z
318'
310
Symbol Detector
322
510
1100

Fig. 11



r
210
508
801 $\mathbf{F}_o$
$(n \times n)$
808
y
810
812
z^{-1} 802
$(\cdot)^*$ 804
$\mathbf{y}_T^*$
A
806
A ∘ B
B
814
702
506
704
814'
Symbol 310 Detector
$\widehat{\Delta\phi}$
322
210
1008'
r
B
A ⊗ B
A
306
z
318
314
316
z^{-1} 302
$(\cdot)^*$ 304
$\mathbf{r}_T^*$
706
1008
318'
Spatial Filter Calculation
$\hat{\mathbf{H}}_o$
Quasi-Coherent Channel Est.
1004
1006
1002
510
1200

Fig. 12



508
210
r
801
$\mathbf{F}_o$
$(n \times n)$
808
810
y
z^{-1}
802
$(\cdot)^*$
804
$\mathbf{y}_T^*$
812
702
B
A
$\mathbf{A} \circ \mathbf{B} / \mathbf{A} \otimes \mathbf{B}$
1102
506
704
814'
Symbol
310
Detector
$\widehat{\Delta\phi}$
322
210
r
314
316
z^{-1}
302
$(\cdot)^*$
304
$\mathbf{r}_T^*$
1008'
z
318'
Spatial Filter
Calculation
$\hat{\mathbf{H}}_o$
Quasi-Coherent
Channel Est.
706
1006
1002
1008
1004
1300

Fig. 13

DIFFERENTIAL MIMO TRANSCEIVER

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is a continuation of U.S. patent application Ser. No. 14/619,612 that was filed Feb. 11, 2015, the entire contents of which are hereby incorporated by reference.

REFERENCE TO GOVERNMENT RIGHTS

This invention was made with government support under 1247583 awarded by the National Science Foundation and FA860-13-C-7351 awarded by the USAF/ESC. The government has certain rights in the invention.

BACKGROUND

In a multiple-input, multiple-output (MIMO) system multiple antennas are used at both the transmitter and the receiver to improve communication performance. MIMO techniques are a key enabler for high-capacity communication at high frequencies, such as millimeter-wave frequencies, that are being developed for emerging 5G wireless applications. Interference between multiple spatial data streams in MIMO systems is a limiting factor that necessitates the use of interference suppression. Linear interference suppression techniques are promising due to their simplicity. However, they generally require coherent channel estimation, which in turn requires the availability of a phase-coherent local oscillator at the receiver. The requirement of phase coherence between the transmitter and receiver is a stringent requirement at high frequencies, adding significant cost and complexity.

SUMMARY

In an example embodiment, a non-transitory computer-readable medium is provided having stored thereon computer-readable instructions that when executed by a computing device, cause the computing device to detect a plurality of information symbols. A first signal is spatially filtered using a spatial filter matrix to define a first filtered signal. The first signal is a result of a first transmitted signal transmitted by a first plurality of antennas and received by a second plurality of antennas connected to the receiver. A conjugate of the first filtered signal is computed to define a conjugate first signal. A second signal is spatially filtered using the spatial filter matrix to define a second filtered signal. The second signal is a result of a second transmitted signal transmitted by the first plurality of antennas and received by the second plurality of antennas connected to the receiver. The second signal is received after the first signal. A Hadamard product is computed of the first filtered signal and the conjugate first signal to define a differential measurement signal. The plurality of information symbols are detected from the differential measurement signal.

In another example embodiment, a receiver is provided that detects a plurality of information symbols.

In yet another example embodiment, a method is provided of detecting a plurality of information symbols.

Other principal features of the disclosed subject matter will become apparent to those skilled in the art upon review of the following drawings, the detailed description, and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Illustrative embodiments of the disclosed subject matter will hereafter be described referring to the accompanying drawings, wherein like numerals denote like elements.

FIG. **1** depicts a communication scenario in accordance with an illustrative embodiment.

FIG. **2** depicts a transmitter and a receiver in a multiple-input, multiple-output (MIMO) system in accordance with an illustrative embodiment.

FIG. **3** depicts a block diagram of a receiver device in accordance with an illustrative embodiment.

FIGS. **4***a*-**4***c* illustrate the performance of five communication systems for three different levels of interference.

FIGS. **5-8** depict block diagrams of receiver devices in accordance with illustrative embodiments.

FIGS. **9***a*-**9***c* illustrate the performance of five communication systems for three different levels of interference.

FIGS. **10-13** depict block diagrams of receiver devices in accordance with additional illustrative embodiments.

DETAILED DESCRIPTION

Referring to FIG. **1**, in an illustrative communication system, there is a line-of-sight (LoS) path between a first transceiver **100** and a second transceiver **102** that represents clear spatial channel characteristics though first transceiver **100** and second transceiver **102** also may be linked in a multipath environment. For example, a signal **104** transmitted by second transceiver **102** is radiated towards first transceiver **100** on the LoS path. First transceiver **100** and second transceiver **102** support both the transmission and the reception of electromagnetic waves. Use of the terms transmitter and receiver is to describe an example function that can be performed by each device. For purposes of discussion, second transceiver **102** is denoted as a transmitting transceiver or a transmitter, and first transceiver **100** is denoted as a receiving transceiver or receiver though each transceiver may be configured to support either or both functions. First transceiver **100** is illustrated as a base station of a communications system and second transceiver **102** is illustrated as a communications device that communicates with the base station such as a cell phone though this is merely for exemplification and is not intended to be limiting.

One or both of first transceiver **100** and second transceiver **102** may be mounted on moving objects such that a distance between the transceivers may change with time. As known to a person of skill in the art, the communication environment between first transceiver **100** and second transceiver **102** may fluctuate due to changes in environmental conditions such as weather, due to changes in interference sources, and due to movement between first transceiver **100** and second transceiver **102**, which may change the multipath environment, any of which may cause a fluctuation in the received signal-to-noise ratio (SNR), signal-to-interference ratio (SIR), signal to interference and noise ratio (SINR), and/or communication channel characteristics, even where the transmission power and other signal characteristics such as frequency, pulsewidth, bandwidth, etc. remain unchanged.

Referring to FIG. **2**, first transceiver **100** may include a plurality of antennas **200** arranged to form an array. The array may be a uniform or a non-uniform linear array, a rectangular array, a circular array, a conformal array, etc. The plurality of antennas **200** are mounted in a common plane. An antenna of the plurality of antennas **200** may be a dipole antenna, a monopole antenna, a helical antenna, a microstrip antenna, a patch antenna, a fractal antenna, a feed horn, a slot antenna, etc. An antenna spacing, denoted d_R, may separate each of the plurality of antennas **200** from an adjacent antenna of the plurality of antennas **200** in the common plane. The plurality of antennas **200** are configured to receive an analog signal from second transceiver **102** and/or to radiate a plurality of radio waves toward second transceiver **102**. The first plurality of antennas **200** may include any number of antennas where M denotes the number of antennas included in the first plurality of antennas **200**.

Second transceiver **102** may include a second plurality of antennas **202** arranged to form a second array. The second array may be a uniform or a non-uniform linear array, a rectangular array, a circular array, a conformal array, etc. The second plurality of antennas **202** are mounted in a common plane. An antenna of the second plurality of antennas **202** may be a dipole antenna, a monopole antenna, a helical antenna, a microstrip antenna, a patch antenna, a fractal antenna, a feed horn, a slot antenna, etc. A second antenna spacing, denoted d_T, may separate each of the second plurality of antennas **202** from an adjacent antenna of the second plurality of antennas **202** in the common plane. The second plurality of antennas **202** are configured to receive an analog signal from first transceiver **100** and/or to radiate a plurality of radio waves toward first transceiver **100**. The second plurality of antennas **202** may include any number of antennas where N denotes the number of antennas included in the second plurality of antennas **202**.

A boresight vector **204** extends from a center of the array of first transceiver **100** perpendicular to the common plane in which the plurality of antennas **200** is mounted. Second transceiver **102** is located along a direction vector **206** which defines an angle **208**, which may be denoted φ_o, relative to boresight vector **204**. For illustration, φ_o represents only the azimuth angle relative to a linear array. Alternative embodiments can be extended to two-dimensional arrays in which the angle φ_o is replaced by a pair of angles representing the azimuth angle and the elevation angle.

In an illustrative embodiment, first transceiver **100** and second transceiver **102** are configured to support differential communication. Differential communication is typically used when a phase-coherent local oscillator is not available at the receiver, resulting in an unknown phase offset between the transmitter and receiver, and possibly even a small frequency offset. In a constant modulus constellation, the transmitted symbols may be of the form $s=Ae^{j\varphi}$ for some given fixed A. Let A=1 for simplicity. In a differential communication system, information is typically encoded in a phase difference $\Delta\varphi$ between a current transmit symbol s=s(t) and a previous transmit symbol $s_T=s(t-T)$ where T is a symbol period; that is,

$$s=Ae^{j\varphi}=e^{j\Delta\varphi}s_T;\ s_T=Ae^{j\varphi_T}. \quad (1)$$

Assuming that the differential symbols $\Delta\varphi$ are chosen randomly from a symmetric constellation, such as in a communication system that uses quadrature phase shift keying (QPSK), and are independent across time, it follows that $e^{j\Delta\varphi}$ is zero mean and independent of s_T. Under these assumptions, the following can be shown:

$$E[s_T]=0;\ E[s]=E[e^{j\varphi}]E[s_T]=0$$

$$|s|^2=|s_T|^2=A^2=1$$

$$ss_T^*=e^{j\Delta\varphi}|s_T|^2;\ E[ss_T^*]=0. \quad (2)$$

This also specifies the second-order statistics of the entire sequence of symbols, under the assumption that the starting symbol, s_0, at time zero satisfies $E[s_0]=0$ and $E[|s_0|^2]=A^2=1$, which is readily satisfied. The received signals r **210** and the differential measurements are

$$r=e^{j\varphi_o}s+v;\ r_T=e^{j\varphi_o}s_T+v_T \quad (3)$$

$$rr_T^*=ss_T^*+sv_T^*+vs_T^*+vv_T^*=e^{j\Delta\varphi}+w, \quad (4)$$

where v and v_T represent noise, and it is assumed that the unknown phase offset φ_o remains constant, or varies sufficiently slowly over consecutive symbols to enable the detection of the differentially encoded symbols $\Delta\varphi$ from rr^*_T in equation (4).

Given a general n×n MIMO system where N=M=n such that second transceiver **102** and first transceiver **100** both include n antennas, the two transmitted signal vectors for the current symbol and the previous symbol corresponding to n differential symbols can be defined as $\Delta\varphi=[\Delta\varphi_1, \Delta\varphi_2, \ldots, \Delta\varphi_n]^T$ and

$$s=[s_1, s_2, \ldots, s_n]^T \quad (5)$$

$$=s(t)=[s_1(t), s_2(t), \ldots, s_n(t)]^T \quad (6)$$

$$s_T=[s_{1_T}, s_{2_T}, \ldots, s_{n_T}]^T \quad (7)$$

$$=s(t-T) \quad (8)$$

$$=[s_1(t-T), s_2(t-T), \ldots, s_n(t-T)]^T \quad (9)$$

The corresponding received signals r, r_T may be defined similarly. The composite 2n×1 transmitted and received signal vectors may be defined as

$$s_c=\begin{bmatrix} s \\ s_T \end{bmatrix};\quad r_c=\begin{bmatrix} r \\ r_T \end{bmatrix}. \quad (10)$$

The overall MIMO system equation for the two symbol vectors and the composite vector is

$$r=Hs,\ r_T=H_Ts_T;\ r_C=H_Cs_C \quad (11)$$

where H=H(t) and $H_T=H(t-T)$ and the 2n×2n composite channel matrix H_C is given by

$$H_c=\begin{bmatrix} H & 0 \\ 0 & H_T \end{bmatrix} \quad (12)$$

In differential communication, it is assumed that $H=H_T$; that is, the channel does not change across two symbol durations. The following differential measurements are possible at the receiver

$$R_c=r_cr_c^H=\begin{bmatrix} rr^H & rr_T^H \\ r_Tr^H & r_Tr_T^H \end{bmatrix} \quad (13)$$

Using equation (11), the system equation for these differential measurements at the receiver (without noise) is

$$R_C=r_Cr_C^H=H_Cs_Cs_C^HH_C^H=H_CQ_CH_C^H \quad (14)$$

where $Q_C=s_Cs_C^H$ is of the same form as equation (13) for $r_Cr_C^H$ and represents the possibilities for differential transmission. Using equation (12) and expanding equation (14) results in

$$R_c=\begin{bmatrix} rr^H & rr_T^H \\ r_Tr^H & r_Tr_T^H \end{bmatrix}=\begin{bmatrix} Hss^HH^H & Hss_T^HH_T^H \\ H_Ts_Ts^HH^H & H_Ts_Ts_T^HH_T^H \end{bmatrix}. \quad (15)$$

The matrix relation defined by equation (15) represents a fundamental set of equations for understanding MIMO communication and interference suppression under differential signaling. Another version can be obtained by vectorizing equation (14) as

$$z_C=\mathrm{vec}(R_C)=[H_C{}^*\otimes H_C]x_C,\ x_C=\mathrm{vec}(Q_C) \quad (16)$$

where the following relation is used

$$\mathrm{vec}(ADB)=[B^T\otimes A]\mathrm{vec}(D) \quad (17)$$

where ⊗ denotes a Kronecker product. A special case of equation (17) for vectors a and b is

$$\mathrm{vec}(ab^H)=[b^*\otimes a]\mathrm{vec}(I_1)=b^*\otimes a \quad (18)$$

A sub-system of equation (15) and equation (16) can be defined as

$$rr_T{}^H=Hss_TH_T{}^H=Hss_TH^H, \quad (19)$$

where the assumption that $H=H_T$ is applied. Vectorizing equation (19) results in

$$z=H_dx;\ H_d=[H^*{}_T\otimes H]$$

$$z=\mathrm{vec}(rr_T{}^H),\ x=\mathrm{vec}(ss_T{}^H) \quad (20)$$

where H_d is a differential-MIMO (D-MIMO) channel matrix. For n=2,

$$rr_T^H=\begin{bmatrix} r_1r_{1T}^* & r_1r_{2T}^* \\ r_2r_{1T}^* & r_2r_{2T}^* \end{bmatrix}, \quad (21)$$

$$ss_T^H=\begin{bmatrix} s_1s_{1T}^* & s_1s_{2T}^* \\ s_2s_{1T}^* & s_2s_{2T}^* \end{bmatrix}, \quad (22)$$

$$z=vec(rr_T^H)=\begin{bmatrix} r_1r_{1T}^* \\ r_2r_{1T}^* \\ r_1r_{2T}^* \\ r_2r_{2T}^* \end{bmatrix} \quad (23)$$

$$x=vec(ss_T^H)=\begin{bmatrix} s_1s_{1T}^* \\ s_2s_{1T}^* \\ s_1s_{2T}^* \\ s_2s_{2T}^* \end{bmatrix}, \text{ and} \quad (24)$$

$$H_d=H_T^*\otimes H=H^*\otimes H \quad (25)$$

$$=\begin{bmatrix} h_{11}^* & h_{12}^* \\ h_{21}^* & h_{22}^* \end{bmatrix}\otimes\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \quad (26)$$

$$=\begin{bmatrix} h_{11}^*H & h_{12}^*H \\ h_{21}^*H & h_{22}^*H \end{bmatrix} \quad (27)$$

$$=\begin{bmatrix} |h_{11}|^2 & h_{11}^*h_{12} & h_{12}^*h_{11} & |h_{12}|^2 \\ h_{11}^*h_{21} & h_{11}^*h_{22} & h_{12}^*h_{21} & h_{12}^*h_{22} \\ h_{21}^*h_{11} & h_{21}^*h_{12} & h_{22}^*h_{11} & h_{22}^*h_{12} \\ |h_{21}|^2 & h_{21}^*h_{22} & h_{22}^*h_{21} & |h_{22}|^2 \end{bmatrix}. \quad (28)$$

H_d is full-rank, if H is full-rank, which follows from the properties of the Kronecker product: rank(A⊗B)=rank(A) rank(B). The first and last elements of z carry the information about the desired differential symbols, $\Delta\varphi_1$ and $\Delta\varphi_2$, contained in the first and last elements of x. The remaining elements of z represent cross-terms that carry information about interference. If there is no inter-channel inference, H is diagonal, there is no interference in the differential system, and H_d is diagonal. The off-diagonal entries of H_d represent the interference between the transmitted signals in x (see equation (24)) that corrupt the receiver measurements in z (see equation (23)).

The noisy underlying system equations based on equation (11) can be defined as

$$r=\sqrt{\rho}Hs+v;\ r_T=\sqrt{\rho}H_Ts_T+v_T \quad (29)$$

$$rr_T{}^H=\rho Hss_T{}^HH_T{}^H+\sqrt{\rho}Hsv_T{}^H+\sqrt{\rho}vs_T{}^HH_T{}^H+vv_T{}^H \quad (30)$$

where $v\sim\mathcal{CN}(0,\sigma^2I_n)$ and $v_T\sim\mathcal{CN}(0,\sigma^2I_n)$ represent complex Gaussian noise vectors that are independent of each other, the signals are s and s_T, and ρ represents a signal-to-noise ratio (SNR) for each data stream. Vectorizing equation (30) results in a noisy version of the D-MIMO system equation (20) and is defined as

$$z=\rho H_dx+w \quad (31)$$

where

$$w=w_1w_2w_3=\mathrm{vec}(\sqrt{\rho}Hsv_T{}^H+\sqrt{\rho}vs_T{}^HH_T{}^H+vv_T{}^H), \quad (32)$$

$x=\mathrm{vec}(ss_T{}^H)$ is the vector of transmitted differential symbols, $z=\mathrm{vec}(rr_T{}^H)$ is a vector of received differential signals, and w is an effective noise vector that consists of the three terms indicated in equation (32).

A $n^2\times n^2$ (4×4 for the illustrative case) matrix F_o can be designed that operates on the vector z to yield estimates of x in which the interference has been suppressed:

$$x_{est}=F_oz. \quad (33)$$

F_o can be defined using a minimum mean squared error (MMSE) criterion, assuming knowledge of the D-MIMO channel matrix H_d as:

$$F_o=\mathrm{argmin}_FE[\|x_{est}-x\|^2]=H_d{}^H(\rho^2H_dH_d{}^{H+\Sigma}{}_w)^{-1} \quad (34)$$

where $\Sigma_W=E[ww^H]$ is a covariance matrix of w, and $H_dH_d{}^H=(H^*{}_TH_T{}^T\otimes HH^H)$. ρ^2 may know a priori in some cases or may be estimated as part of channel estimation using training signals as understood by a person of skill in the art. F_o is a spatial filter matrix that is ($n^2\times n^2$).The differentially encoded transmitted symbols in x can be estimated at the receiver by applying differential detectors, corresponding to the differential transmission scheme used, to the appropriate elements of x_{est}.

To characterize the second-order statistics of x and w in equation (31), zero-mean signal constellations for the differential symbols is assumed with different differential symbols assumed to be independent across time and data streams. This results in the following second-order statistics for s:

$$E[s]=E[s_T]=0,\ E[ss_T{}^H]=0 \quad (35)$$

$$E[ss^H]=E[s_Ts_T{}^H]=I_n \quad (36)$$

which in turn results in the following second-order statistics for $x=\mathrm{vec}(ss_T{}^H)$

$$E[X]=E[vec(ss_T^H)]=vec(E[ss_T^H])=0 \quad (37)$$

-continued

$$E[xx^H] = E\left[vec(ss_T^H)vec(ss_T^H)^H\right] = E[(s_T^*\otimes s)(s_T^T\otimes s^H)] = E[s^*s_T^T\otimes ss^H] = E[s^*s_T^T]\otimes E[ss^H] = I_n\otimes I_n = I_{n^2}.$$

Assuming that the signal and noise are independent, and using the assumptions on the statistics of v and v_T, it can be shown that

$$E[w] = 0 \tag{38}$$

$$\Sigma_w = E[ww^H] = \rho\sigma^2(I_n\otimes HH^H) + \rho\sigma^2(H_T^*H_T^T\otimes I_n) + \sigma^4 I_{n^2} \tag{39}$$

where the three terms in Σ_W in equation (39) represent the covariance matrices of the corresponding terms in equation (32), where σ^2 is a noise power.

The noise statistics follow from the following calculations on the joint statistics of w_1, w_2, and w_3 in equation (32). Using equation (18),

$$w_1=\sqrt{\rho}\text{vec}(Hsv_T^H)=\sqrt{\rho}(v_T^*\otimes Hs) \tag{40}$$

$$w_2=\sqrt{\rho}\text{vec}(vs_T^H H_T^H)=\sqrt{\rho}(H_T^*s_T^*\otimes v) \tag{41}$$

$$w_3=\text{vec}(vv_T^H)=(v_T^*\otimes v). \tag{42}$$

The second-order statistics of $\{w_i\}$ are

$$E[w_1] = \sqrt{\rho}\,(E[v_T^*]\otimes E[Hs]) = 0 \tag{43}$$

$$E[w_1w_1^H] = \rho E[(v_T^*\otimes Hs)(v_T^*\otimes Hs)^H] = \rho E[(v_T^*v_T^T\otimes Hss^H H)] = \rho\sigma^2 E[v_T^*v_T^T]\otimes HE[ss^H]H^H = \rho\sigma^2 I_n\otimes HH^H. \tag{44}$$

Similarly,

$$E[w_2]=E[w_3]=0 \tag{45}$$

$$E[w_2w_2^H]=\rho\sigma^2(H_T^*H_T^H\otimes I_n) \tag{46}$$

$$E[w_3w_3^H]=\sigma^2 I_n\otimes\sigma^2 I_n=\sigma^4 I_{n^2}. \tag{47}$$

It can further be similarly shown that

$$E[w_1w_2^H]=E[w_1w_3^H]=E[w_2w_3^H]=0. \tag{48}$$

Combining the above calculations leads to the second-order statistics of w given in equation (39).

If HH^H has the eigenvalue decomposition $HH^H=U\Lambda U^H$ and $H_TH_T^H$ has the eigenvalue decomposition $H_TH_T^H=U_T\Lambda_TU_T^H$, the noise covariance matrix Σ_W has the eigenvalue decomposition

$$\Sigma_W=(U^*_T\otimes U)\tilde{\Lambda}(U^*_T\otimes U)^H \tag{49}$$

$$\tilde{\Lambda}=\rho\sigma^2(\Lambda\oplus\Lambda_T)+\sigma^4 I_{n^2} \tag{50}$$

where $A\oplus B=(I\otimes A)+(B\otimes I)$ is the Kronecker sum.

H_d can be estimated using training symbols as understood by a person of skill in the art. The estimated version of channel matrix H_d is plugged into equation (34) to determine spatial filter matrix F_o. The training signals can be designed in a variety of ways. The simplest approach may be to design the transmitted signals so that only one entry of x (see equation (24)) is non-zero in each differential training symbol; the corresponding column of H_d can then be estimated from the corresponding received differential measurements z (see equation (23). The training symbols that correspond to this simple approach are described below. For estimating the first column of H_d, the following may be transmitted

$$s = s_T = \begin{bmatrix}1\\0\end{bmatrix} \tag{51}$$

resulting in

$$x = \begin{bmatrix}1\\0\\0\\0\end{bmatrix}. \tag{52}$$

For estimating the second column of H_d, the following may be transmitted

$$s = \begin{bmatrix}0\\1\end{bmatrix}, s_T = \begin{bmatrix}1\\0\end{bmatrix} \tag{53}$$

resulting in

$$x = \begin{bmatrix}0\\1\\0\\0\end{bmatrix}. \tag{54}$$

For estimating the third column of H_d, the following may be transmitted

$$s = \begin{bmatrix}1\\0\end{bmatrix}, s_T = \begin{bmatrix}0\\1\end{bmatrix} \tag{55}$$

resulting in

$$x = \begin{bmatrix}0\\0\\1\\0\end{bmatrix}. \tag{56}$$

Finally, for estimating the fourth column of H_d, the following may be transmitted

$$s = s_T = \begin{bmatrix}0\\1\end{bmatrix} \tag{57}$$

resulting in

$$x = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}. \quad (58)$$

From equation (39) estimates of HH^H and $H^*_T H_T^T$ are used to estimate Σ_W for F_o in equation (34). For a case of interest, $H_T=H$, so that

$$\mathrm{vec}(HH^H)=[H^*\otimes H]\mathrm{vec}(I)=H_d\mathrm{vec}(I). \quad (59)$$

As a result, the two matrices HH^H and $H^*_T H_T^T$ can be extracted from H_d.

Referring to FIG. **3**, a block diagram of a receiver **300** that may be implemented at first transceiver **100** acting as a receiving transceiver is shown in accordance with an illustrative embodiment. Second transceiver **102** may include similar elements as understood by a person of skill in the art. Receiver **300** may be implemented to yield estimates of x, an estimate vector x_{est}, in which the interference has been suppressed by defining matrix F_o that operates on the vector z as defined in equation (33). Receiver **300** may include a sample and hold operator **302**, a conjugate operator **304**, a Kronecker product operator **306**, a spatial filter operator **308**, and a symbol detector operator **310**. Fewer, different, and additional components may be incorporated into receiver **300**. For example, sample and hold operator **302** may be implemented with a delay line in an analog implementation rather than specifically a sample and hold circuit.

Sample and hold operator **302**, conjugate operator **304**, Kronecker product operator **306**, spatial filter operator **308** and/or symbol detector operator **310** perform operations on a received signal r **210** to detect the differentially encoded symbol vector $\Delta\varphi$ from rr^*_T. One or more of sample and hold operator **302**, conjugate operator **304**, Kronecker product operator **306**, spatial filter operator **308** and/or symbol detector operator **310** may be implemented by a special purpose computer, logic circuits, or hardware circuits as understood by a person of skill in the art. Thus, one or more of the operators may be implemented using hardware, firmware, software, or any combination of these methods, depending on the stage at which the signal is converted from analog to digital form. Furthermore, some of these operators may be implemented in analog (passband) domain, or in the baseband domain. For example, one or more of sample and hold operator **302**, conjugate operator **304**, Kronecker product operator **306**, spatial filter operator **308** and/or symbol detector operator **310** may be implemented in software (comprised of computer-readable and/or computer-executable instructions) stored in a computer-readable medium and accessible by a processor for execution of the instructions that embody the operations of the associated operator. The instructions may be written using one or more programming languages, assembly languages, scripting languages, etc.

A computer-readable medium is an electronic holding place or storage for information so the information can be accessed by the processor as understood by those skilled in the art. The computer-readable medium can include, but is not limited to, any type of random access memory (RAM), any type of read only memory (ROM), any type of flash memory, etc. such as magnetic storage devices (e.g., hard disk, floppy disk, magnetic strips, . . .), optical disks (e.g., compact disc (CD), digital versatile disc (DVD), . . .), smart cards, flash memory devices, etc. Controller **102** may have one or more computer-readable media that use the same or a different memory media technology. Receiver **300** may include one or more computer-readable media.

A processor performs operations as understood by those skilled in the art. A digital signal processor (DSP) is a type of processor that operates on digital signals. The processor may be implemented in hardware and/or firmware. The processor may execute an instruction, meaning the processor performs/controls the operations called for by that instruction. The term "execution" is the process of running an application or the carrying out of the operation called for by an instruction. The processor operably couples with the computer-readable medium to read, to store, and to process information. The processor may retrieve a set of instructions from a permanent memory device and copy the instructions in an executable form to a temporary memory device that is generally some form of RAM. Receiver **300** may include a plurality of processors that use the same or a different processing technology.

Sample and hold operator **302** samples and holds a copy of a previously received signal r_T **314**. Conjugate operator **304** may compute a complex conjugate of the sampled and held previously received signal r_T **314** as a conjugate signal, r^*_T **316**. Kronecker product operator **306** computes a differential measurement signal z **318**, $z=\mathrm{vec}(rr_T^H)=r_T\otimes r$. Spatial filter operator **308** operates on differential measurement signal z **318** to yield estimates of x, an estimate vector x_{est} **320**, in which the interference has been suppressed by applying equation (33), $x_{est}=F_o z$. As discussed above, F_o is a spatial filter matrix that can be defined using equation (34) based on knowledge of the estimated D-MIMO channel matrix H_d, which can be estimated using training symbols as discussed above with reference to equations (51)-(58). Symbol detector operator **310** detects the differentially encoded symbols $\Delta\varphi$ **322**, for example, by applying differential detectors to the estimates of x, estimate vector x_{est} **320**.

To illustrate the performance, probability of error P_e versus SNR for receiver **300** implemented as an n×n MIMO system with n=2 antennas was calculated based on uncoded QPSK differential transmissions. The P_e was computed numerically from 1,000,000 symbols, and the phases of the entries of H were changed randomly every 1,000 symbols. Five different receiver systems were simulated: 1) receiver **300** based on estimating channel matrix H_d using training symbols at the same SNR as that for data communication, 2) receiver **300** assuming perfect channel state information, e.g., perfect knowledge of H_d, 3) a receiver without interference suppression ($F_o=I_n 2$), 4) a coherent system corresponding to two non-interfering QPSK data streams, and 5) a corresponding differential system. FIGS. **4***a*-**4***c* illustrate the performance of the five systems for 3 different levels of interference. In FIG. **4***a*, the interference is strongest: $|h_{12}|^2$ and $|h_{21}|^2$ are 3 decibels (dB) below $|h_{11}|^2=|h_{22}|^2$. In FIG. **4***b*, the interference is 6 dB below the signal. In FIG. **4***c*, the interference is 10 dB below the signal.

Referring to FIG. **4***a*, a first curve **400** shows the results for receiver configuration **1**); a second curve **402** shows the results for receiver configuration **2**); a third curve **404** shows the results for receiver configuration **3**); a fourth curve **406** shows the results for receiver configuration **4**); and a fifth curve **408** shows the results for receiver configuration **5**). Referring to FIG. **4***b*, a first curve **410** shows the results for receiver configuration **1**); a second curve **412** shows the results for receiver configuration **2**); a third curve **414** shows the results for receiver configuration **3**); a fourth curve **416** shows the results for receiver configuration **4**); and a fifth curve **418** shows the results for receiver configuration **5**).

Referring to FIG. **4***c*, a first curve **420** shows the results for receiver configuration **1**); a second curve **422** shows the results for receiver configuration **2**); a third curve **424** shows the results for receiver configuration **3**); a fourth curve **426** shows the results for receiver configuration **4**); and a fifth curve **428** shows the results for receiver configuration **5**). The coherent system of receiver configuration **4**) exhibited the best performance. Receiver configuration **5**), the differential system, had a 3 dB loss compared to the coherent system of receiver configuration **4**). Receiver configuration **2**) exhibited the next best performance relative to receiver configuration **5**). Receiver configuration **1**) exhibited the next best performance relative to receiver configuration **2**). The worst performance is that of receiver configuration **3**) without interference suppression. Receiver configurations **1**) and **2**) provide very competitive performance, whereas ignoring interference can result in unacceptably high P_e. Receiver configurations **4** and **5** are idealized configurations corresponding to an interference-free system for comparison.

Referring to FIG. **5**, a block diagram of a second receiver **500** that may be implemented at first transceiver **100** acting as a receiving transceiver is shown in accordance with an illustrative embodiment. Second transceiver **102** may include similar elements as understood by a person of skill in the art. Similar to receiver **300**, second receiver **500** may be implemented to yield estimates of x, estimate vector x_{est}, in which the interference has been suppressed by defining spatial matrix F_o that operates on differential measurement signal z as defined in equation (33). Second receiver **500** illustrates a completely digital implementation of receiver **300** where all of the receiver operations are performed using a DSP **510**. Second receiver **500** may include a local oscillator **502**, a mixer **504**, an analog-to-digital converter (ADC) **506**, sample and hold operator **302**, conjugate operator **304**, Kronecker product operator **306**, spatial filter operator **308**, symbol detector operator **310**. Fewer, different, and additional components may be incorporated into second receiver **500**.

Received signal r **210** is mixed with a local oscillator signal **503** generated by local oscillator **502** to form a mixed signal **505**. Local oscillator **502** and mixer **504** downmix the received passband signal, received signal r **210**, to baseband. Mixed signal **505** is input to ADC **506**, which converts mixed signal **505** to a digital, baseband signal r **210'**. Sample and hold operator **302**, conjugate operator **304**, Kronecker product operator **306**, spatial filter operator **308** and symbol detector operator **310** are configured to operate on the digital, baseband version of received signal r **210**.

Again, sample and hold operator **302** samples and holds a copy of a previously received digital signal r_T **314'**. Conjugate operator **304** computes a complex conjugate of the sampled and held previously received digital signal r_T **314'** as digital conjugate signal r^*_T **316'**. Kronecker product operator **306** computes a digital, differential measurement signal z **318'**. Spatial filter operator **308** operates on digital, differential measurement signal z **318'** to yield digital estimates of x, a digital estimate vector x_{est} **320'**, in which the interference has been suppressed by applying equation (33), $x_{est}=F_o z$. Symbol detector operator **310** detects the differentially encoded symbols $\Delta\varphi$ **322** from digital estimate vector x_{est} **320'**.

Second receiver **500** further may include a switch **508**, a differential channel estimation operator **512**, and a spatial filter calculation operator **514**. Switch **508**, differential channel estimation operator **512**, and spatial filter calculation operator **514** may also be implemented using DSP **510**. A position of switch **508** depends on whether second receiver **500** is in a channel estimation phase or a data communication phase. The data communication phase is illustrated in FIG. **5** based on the position of switch **508**. In the channel estimation phase, training data, for example, as discussed with reference to equations (51)-(58), is received. In the channel estimation phase, digital, differential measurement signal z **318'** generated by the training data, is provided to differential channel estimation operator **512**, which computes an estimate of channel matrix H_d **516** input to spatial filter calculation operator **514**. Spatial filter calculation operator **514** computes spatial filter matrix F_o **518** using equation (34) based on estimated channel matrix H_d **516** and provides F_o **518** to spatial filter operator **308** for use in the data communication phase.

Referring to FIG. **6**, a block diagram of a third receiver **600** that may be implemented at first transceiver **100** acting as a receiving transceiver is shown in accordance with an illustrative embodiment. Second transceiver **102** may include similar elements as understood by a person of skill in the art. Similar to receiver **300**, third receiver **600** may be implemented to yield estimate vector x_{est}, in which the interference has been suppressed by defining spatial filter matrix F_o that operates on differential measurement signal z **318** as defined in equation (33). Third receiver **600** illustrates an implementation in which the differential measurements, $z=\mathrm{vec}(rr_T^H)=r_T^*\otimes r$, are performed using analog passband devices. Local oscillator **502** and mixer **504** are not needed. Third receiver **600** may include sample and hold operator **302**, conjugate operator **304**, Kronecker product operator **306**, ADC **506**, switch **508**, spatial filter operator **308**, symbol detector operator **310**, differential channel estimation operator **512**, and spatial filter calculation operator **514**. Fewer, different, and additional components may be incorporated into third receiver **600**.

Differential measurement signal z **318** is input to ADC **605**, which converts signal z **318** to digital, differential measurement vector z **318'**. The remaining receiver operators, spatial filter operator **308**, symbol detector operator **310**, differential channel estimation operator **512**, and spatial filter calculation operator **514** are implemented using DSP **510** similar to second receiver **500**.

The data communication phase is illustrated in FIG. **6** based on the position of switch **508**. In the channel estimation phase, training data, for example, as discussed with reference to equations (51)-(58), is received. Switch **508** is positioned to switch digital, differential measurement signal z **318'** output from ADC **506** to differential channel estimation operator **512** during the channel estimation phase. Similar to second receiver **500**, in the channel estimation phase, digital, differential measurement signal z **318'** generated by the training data, is provided to differential channel estimation operator **512**, which computes an estimate of channel matrix H_d **516** input to spatial filter calculation operator **514**. Spatial filter calculation operator **514** computes spatial filter matrix F_o **518** using equation (34) based on estimated channel matrix H_d **516** and provides F_o **518** to spatial filter operator **308** for use in the data communication phase.

Referring to FIG. **7**, a block diagram of a fourth receiver **700** that may be implemented at first transceiver **100** acting as a receiving transceiver is shown in accordance with an illustrative embodiment. Second transceiver **102** may include similar elements as understood by a person of skill in the art. Similar to receiver **300**, fourth receiver **700** may be implemented to yield estimate vector x_{est}, in which the interference has been suppressed by defining spatial filter matrix F_o that operates on differential measurement signal z **318** as defined in equation (33).

Fourth receiver **700** illustrates an implementation in which the differential measurements and the spatial filtering are performed with analog passband and baseband devices, respectively. Again, local oscillator **502** and mixer **504** are not needed. Fourth receiver **700** may include sample and hold operator **302**, conjugate operator **304**, Kronecker product operator **306**, switch **506**, spatial filter operator **308**, ADC **506**, symbol detector operator **310**, differential channel estimation operator **512**, spatial filter calculation operator **514**, a second switch **702**, a third switch **704**, and a digital-to-analog converter (DAC) **706**. Fewer, different, and additional components may be incorporated into fourth receiver **700**.

Estimate vector x_{est} **320** is input to ADC **506**, which converts estimate vector x_{est} **320** to digital estimate vector x_{est} **320'** that is input to symbol detector operator **310**. The remaining receiver operators, symbol detector operator **310**, differential channel estimation operator **512**, and spatial filter calculation operator **514** are performed using DSP **510** similar to second receiver **500**. Switch **508** is positioned to switch differential measurement signal z **318** between spatial filter operator **308** and differential channel estimation operator **512**. Second switch **702** is positioned between spatial filter operator **308** and ADC **506**. Third switch **704** is positioned between ADC **506** and symbol detector operator **310**. Switch **508**, second switch **702**, and third switch **704** switch simultaneously so that, in the channel estimation phase, differential measurement signal z **318** is input to ADC **506** and digital, differential measurement signal z **318'** is input to differential channel estimation operator **512**, which computes the estimate of channel matrix H_d **516** input to spatial filter calculation operator **514**. Spatial filter calculation operator **514** computes spatial filter matrix F_o **518** using equation (34) based on channel matrix H_d **516** and provides spatial filter matrix F_o **518** to DAC **706**, which generates an analog, baseband spatial filter matrix F_o **518'** to spatial filter operator **308** for use in the data communication phase.

A quasi-coherent estimate of a second channel matrix H can be obtained from channel matrix H_d and can be used for linear interference suppression on direct receiver measurements r and r_T, rather than on $z=\mathrm{vec}(rr_T^H)$ followed by differential detection from appropriate elements of z. The following channel decomposition of second channel matrix H can be defined

$$H=H_o\wedge_\varphi \tag{60}$$

where H is the actual channel matrix

$$H=\begin{bmatrix} |h_{11}|e^{j\angle h_{11}} & |h_{12}|e^{j\angle h_{12}} \\ |h_{21}|e^{j\angle h_{21}} & |h_{22}|e^{j\angle h_{22}} \end{bmatrix}, \tag{61}$$

A third channel matrix H_o is what can be estimated from channel matrix H_d as defined below

$$H_O=\begin{bmatrix} |h_{11}| & |h_{12}|e^{j(\angle h_{12}-\angle h_{22})} \\ |h_{21}|e^{j(\angle h_{21}-\angle h_{11})} & |h_{22}| \end{bmatrix}, \tag{62}$$

and $\wedge_\varphi$ is a diagonal matrix defined as $\wedge_\varphi=\mathrm{diag}(e^{j\angle h}\mathbf{11}, e^{j\angle h}\mathbf{22})$. H_o can be estimated from H_d based on equation (27). The first column of $h_{11}^*H/|h_{11}|$ yields the first column of third channel matrix H_o. Similarly, the second column of $h_{22}^*H/|h_{22}|$ yields the second column of third channel matrix H_o. Thus, when using the simple channel estimation approach described by equations (51) and (57), in the quasi-coherent case only the training symbols in equations (51) and (57) are needed to estimate the first and fourth columns of channel matrix H_d needed to determine third channel matrix H_o.

An MMSE filter matrix F is defined by

$$F=H^H(\rho HH^H+\sigma^2 I_n)^{-1}=\wedge_\varphi{}^H H_o{}^H(\rho H_o H_o{}^H+\sigma^2 I_n)^{-1}=\wedge_\varphi{}^H F_o, \tag{63}$$

which operates on the baseband signal vector r. A second spatial filter matrix F_o in equation (6) can be computed at the receiver and used for interference suppression. Thus, the processed signal vector from which the differentially encoded symbols are detected can be defined by

$$y=F_o r=F_o Hs+F_o v, \tag{64}$$

The use of second spatial filter matrix F_o, rather than MMSE filter matrix F, does not impact the ability to detect differential symbols since the i-th differentially encoded transmitted symbol in $s_i s_{iT}^*$ is detected from the product $y_i y_{iT}^*$, which corresponds to detecting the differentially encoded symbol vector via $y \circ y_T^*$ where $\circ$ denotes the Hadamard (element-wise) product. Second spatial filter matrix F_o has order (n×n) rather than the order (n^2×n^2) of spatial filter matrix F_o defined for receivers **300**, **500**, **600**, and **700**.

Interference suppression using precoding at the transmitter is also possible. In reciprocal channels, if the transmitter first acts as a receiver and estimates the channel matrix from differential measurements based on training symbols from the receiver, the following decomposition of second channel matrix H results

$$H=\wedge_\varphi H_o, \tag{65}$$

In this case, the transmitted signal may be precoded as $s \rightarrow Gs_V$ where

$$G=\alpha F,\ \alpha=\sqrt{\rho/\mathrm{tr}(F\wedge_S F^H)}$$

$$F=(H^H H+\zeta I)^{-1}H^H,\ \zeta=\sigma^2/\rho, \tag{66}$$

where s_V is the symbol vector, ρ represents transmit power (SNR if $\sigma^2=1$) per data stream, and $\wedge_S=E[ss^H]$ is a diagonal covariance matrix of transmitted symbols, which is $\wedge_S=I$, and where tr(A) denotes the trace of a square matrix A, which is the sum of the diagonal entries of A. The composite system matrix with precoding can be defined as

$$r=HGs+v \tag{67}$$

and the composite matrix HG controls the interference. In terms of third channel matrix H_o, F is defined by

$$F=(H_o{}^H H_{o+\zeta I})^{-1}H_o{}^H\wedge_\varphi{}^*=F_o\wedge_\varphi{}^* \tag{68}$$

where second spatial filter matrix F_o can be computed based on third channel matrix H_o. The unknown phases in $\wedge_\varphi{}^*$ are inconsequential from the viewpoint of differential signaling, and the receiver can directly detect the symbols differentially from $z=\mathrm{vec}(rr_T^H)$ because interference suppression is performed at the transmitter.

Referring to FIG. **8**, a block diagram of a fifth receiver **800** that may be implemented at first transceiver **100** acting as a receiving transceiver is shown in accordance with an illustrative embodiment. Fifth receiver **800** may be referred to as an example of a quasi-coherent receiver that suppresses interference. Second transceiver **102** may include similar elements as understood by a person of skill in the art. Fifth receiver **800** may be implemented to define second spatial filter matrix F_o that operates on received signal r **210** as defined in equation (64). Fifth receiver **800** may include a second spatial filter operator **801**, a second sample and hold operator **802**, a second conjugate operator **804**, a Hadamard product operator **806**, and symbol detector operator **310**. Fewer, different, and additional components may be incorporated into fifth receiver **800**.

Similar to sample and hold operator **302**, conjugate operator **304**, Kronecker product operator **306**, and spatial filter operator **308**, second spatial filter operator **801**, second sample and hold operator **802**, second conjugate operator **804**, and Hadamard product operator **806** may be implemented by a special purpose computer, logic circuits, or hardware circuits (analog or digital) as understood by a person of skill in the art. Thus, second spatial filter operator **801**, second sample and hold operator **802**, second conjugate operator **804**, and Hadamard product operator **806** may be implemented using hardware, firmware, software, or any combination of these methods. For example, second spatial filter operator **801**, second sample and hold operator **802**, second conjugate operator **804**, and Hadamard product operator **806** may be implemented in software (comprised of computer-readable and/or computer-executable instructions) stored in a computer-readable medium and accessible by a processor for execution of the instructions that embody the operations of the associated operator. The instructions may be written using one or more programming languages, assembly languages, scripting languages, etc. Fifth receiver **800** may include one or more computer-readable media. Fifth receiver **800** may include a plurality of processors that use the same or a different processing technology.

Both Hadamard product operator **806** and Kronecker product operator **306** generate differential measurements between a current and a previous measurement. Hadamard product operator **802** performs operations $y \circ y_T^*$ where $\circ$ denotes the Hadamard element-wise product.

Second spatial filter operator **801** operates on the received signal r **210** to yield $y=F_o r=F_o Hs+F_o v$. Second spatial filter matrix F_o can be defined using equation (63) based on an estimate of third channel matrix H_o determined using equation (62) based on an estimate of channel matrix H_d, which can be estimated using training symbols as discussed above with reference to equations (51)-(58). Second sample and hold operator **802** samples and holds a copy of a previously filtered signal y_T **808**. Second conjugate operator **804** computes a complex conjugate of the sampled and held previously filtered signal y_T **810** as conjugate signal y^*_T **812**. Hadamard product operator **806** computes differential measurement signal $y \circ y_T^*$ **814**. Symbol detector operator **310** detects the differentially encoded symbols $\Delta\varphi$ **322** from differential measurement signal $y \circ y_T^*$ **814**, for example, by applying differential detectors.

To illustrate the performance, probability of error P_e versus SNR for fifth receiver **800** implemented as an n×n MIMO system with n=2 antennas was calculated based on uncoded QPSK differential transmissions. The P_e was computed numerically from 1,000,000 symbols, and the phases of the entries of H were changed randomly every 1,000 symbols. Five different receiver systems were simulated: 1) fifth receiver **800** based on estimating H_d using training symbols at the same SNR as that for data communication, 2) fifth receiver **800** assuming perfect channel state information, e.g., perfect knowledge of H_d, 3) a receiver without interference suppression ($F_o=I_{n^2}$), 4) a coherent system corresponding to two non-interfering QPSK data streams, and 5) a corresponding differential system. FIGS. **9***a*-**9***c* illustrate the performance of the five systems for 3 different levels of interference.

In FIG. **9***a*, the interference is strongest: $|h_{12}|^2$ and $|h_{21}|^2$ are 3 decibels (dB) below $|h_{11}|^2=|h_{22}|^2$. In FIG. **9***b*, the interference is 6 dB below the signal. In FIG. **9***c*, the interference is 10 dB below the signal. Referring to FIG. **9***a*, a first curve **900** shows the results for receiver configuration **1**); a second curve **902** shows the results for receiver configuration **2**); a third curve **904** shows the results for receiver configuration **3**); a fourth curve **906** shows the results for receiver configuration **4**); and a fifth curve **908** shows the results for receiver configuration **5**). Referring to FIG. **9***b*, a first curve **910** shows the results for receiver configuration **1**); a second curve **912** shows the results for receiver configuration **2**); a third curve **914** shows the results for receiver configuration **3**); a fourth curve **916** shows the results for receiver configuration **4**); and a fifth curve **918** shows the results for receiver configuration **5**). Referring to FIG. **9***c*, a first curve **920** shows the results for receiver configuration **1**); a second curve **922** shows the results for receiver configuration **2**); a third curve **924** shows the results for receiver configuration **3**); a fourth curve **926** shows the results for receiver configuration **4**); and a fifth curve **928** shows the results for receiver configuration **5**). The coherent system of receiver configuration **4**) exhibited the best performance. Receiver configuration **5**), the differential system, had a 3 dB loss compared to the coherent system of receiver configuration **4**). Receiver configuration **2**) exhibited the next best performance relative to receiver configuration **5**). Receiver configuration **1**) exhibited the next best performance relative to receiver configuration **2**). The worst performance is that of receiver configuration **3**) without interference suppression. Receiver configurations **1**) and **2**) provide very competitive performance, and are comparable to receiver configurations **1**) and **2**) using receiver **300**. Receiver configuration **1**) using receiver **300** performs slightly worse than receiver configuration **1**) using fifth receiver **800**.

FIGS. **10**-**13** show implementations of a quasi-coherent MIMO receiver based on fifth receiver **800**. Because the quasi-coherent MIMO receiver uses cross-channel and co-channel differential measurements during the channel estimation phase and only co-channel differential measurements during the data communication phase, the Hadamard product is computed during the data communication phase and the Kronecker product is computed during the channel estimation phase.

Referring to FIG. **10**, a block diagram of a sixth receiver **1000** that may be implemented at first transceiver **100** acting as a receiving transceiver is shown in accordance with an illustrative embodiment. Second transceiver **102** may include similar elements as understood by a person of skill in the art. Similar to fifth receiver **800**, sixth receiver **1000** may be implemented to define second spatial filter matrix F_o that operates on received signal r **210** as defined in equation (64). Sixth receiver **1000** illustrates a completely digital implementation where all of the receiver operations are performed using DSP **510**.

Similar to second receiver **500**, sixth receiver **1000** may include local oscillator **502**, mixer **504**, ADC **506**, and switch **508**. Received signal r **210** is mixed with local oscillator signal **503** generated by local oscillator **502** to form mixed signal **505**. Local oscillator **502** and mixer **504** downmix the received passband signal, received signal r **210**, to baseband. Mixed signal **505** is input to ADC **506**, which converts mixed signal **505** to digital, baseband signal r 210'. Similar to second receiver **500**, sixth receiver **1000** further may include switch **508** that is switched between the data communication phase shown in FIG. **10** and the channel estimation phase.

Similar to fifth receiver **800**, sixth receiver **1000** may include second spatial filter operator **801**, second sample and hold operator **802**, second conjugate operator **804**, Hadamard product operator **806**, and symbol detector operator **310** used in the data communication phase. Each of second spatial filter operator **801**, second sample and hold operator **802**, second conjugate operator **804**, Hadamard product operator **806**, and symbol detector operator **310** is implemented using DSP **510** and connected as discussed with reference to FIG. **8** to receive and process digital, baseband signal r **210'** to detect the differentially encoded symbols $\Delta\varphi$ **322**. The signals processed by second spatial filter operator **801**, second sample and hold operator **802**, second conjugate operator **804**, Hadamard product operator **806**, and symbol detector operator **310** are configured to operate on digital signals.

Similar to second receiver **500**, sixth receiver **1000** further may include sample and hold operator **302**, conjugate operator **304**, Kronecker product operator **306** connected to receive and process digital, baseband signal r **210'**. To support the channel estimation phase, sixth receiver **1000** further may include a quasi-coherent channel estimation operator **1002** and a second spatial filter computational operator **1004**. Quasi-coherent channel estimation operator **1002** generates an estimate of third channel matrix H_o **1006** from a computation of channel matrix H_d based on equation (27). For example, quasi-coherent channel estimation operator **1002** first implements differential channel estimation operator **512** to estimate channel matrix H_d **516** and then estimates third channel matrix H_o **1006** from channel matrix H_d **516**. Second spatial filter computational operator **1004** computes second spatial filter matrix F_o **1008** in digital form from third channel matrix H_o **1006** using equation (63) and provides the computation to second spatial filter operator **801**. Fewer, different, and additional components may be incorporated into sixth receiver **1000**.

Referring to FIG. **11**, a block diagram of a seventh receiver **1100** that may be implemented at first transceiver **100** acting as a receiving transceiver is shown in accordance with an illustrative embodiment. Second transceiver **102** may include similar elements as understood by a person of skill in the art. Similar to fifth receiver **800**, seventh receiver **1100** may be implemented to define second spatial filter matrix F_o that operates on received signal r **210** as defined in equation (64). Seventh receiver **1100** also illustrates a completely digital implementation where all of the receiver operations are performed using DSP **510**.

Seventh receiver **1100** differs from sixth receiver **1000** in that seventh receiver **1100** includes a configurable product operator **1102**, second switch **702**, and third switch **704**. Second switch **702** is positioned on an input side of configurable product operator **1102**, and third switch **704** is positioned on an output side of configurable product operator **1102**. Switch **508**, second switch **702**, and third switch **704** are switched simultaneously to switch between the data communication phase shown in FIG. **11** and the channel estimation phase. Configurable product operator **1102** is configured to perform the Hadamard product in the data communication phase and to perform the Kronecker product in the channel estimation phase. As a result, the inputs to configurable product operator **1102** are switched between the digital filtered inputs **808'**, **812'** provided to compute the Hadamard product and the digital unfiltered inputs **210'** and **316'** provided to compute the Kronecker product, and the outputs from configurable product operator **1102** are switched between digital, differential measurement signal $y \circ y_T^*$ **814'** and digital, differential measurement signal z **318'**. Digital, differential measurement signal $y \circ y_T^*$ **814'** is input to symbol detector **310**. Digital, differential measurement signal z **318'** is input to quasi-coherent channel estimation operator **1002**.

Referring to FIG. **12**, a block diagram of an eighth receiver **1200** that may be implemented at first transceiver **100** acting as a receiving transceiver is shown in accordance with an illustrative embodiment. Second transceiver **102** may include similar elements as understood by a person of skill in the art. Similar to fifth receiver **800**, eighth receiver **1200** may be implemented to define second spatial filter matrix F_o that operates on received signal r **210** as defined in equation (64). Eighth receiver **1200** illustrates an implementation similar to fourth receiver **700** in that the spatial filtering and differential measurements are performed by analog devices, and the channel estimation, spatial filter computation, and symbol detection are performed by digital devices.

Referring to FIG. **13**, a block diagram of a ninth receiver **1300** that may be implemented at first transceiver **100** acting as a receiving transceiver is shown in accordance with an illustrative embodiment. Second transceiver **102** may include similar elements as understood by a person of skill in the art. Similar to fifth receiver **800**, may be implemented to define second spatial filter matrix F_o that operates on received signal r **210** as defined in equation (64). Ninth receiver **1300** also illustrates an implementation similar to fourth receiver **700** in that the spatial filtering and differential measurements are performed by analog devices, and the channel estimation, spatial filter computation, and symbol detection are performed by digital devices. Ninth receiver **1300** differs from eighth receiver **1200** in that configurable product operator **1102** replaces separate Kronecker product operator **306** and Hadamard product operator **806**. The inputs to configurable product operator **1102** are switched between the filtered inputs **808**, **812** provided to compute the Hadamard product and the unfiltered inputs **210** and **316** provided to compute the Kronecker product, and the outputs from configurable product operator **1102** are switched between digital, differential measurement signal $y \circ y_T^*$ **814'** and digital, differential measurement signal z **318'**. Digital, differential measurement signal $y \circ y_T^*$ **814'** is input to symbol detector **310**. Digital, differential measurement signal z **318'** is input to quasi-coherent channel estimation operator **1002**.

FIGS. **10** and **12** show implementations where Hadamard product operator **802** and Kronecker product operator **306** are implemented separately. FIGS. **11** and **13** show implementations where Hadamard product operator **802** and Kronecker product operator **306** are implemented by configurable product operator **1102** that can be switched between full and reduced differential measurements based on the channel estimation phase or the data communication phase. FIGS. **10** and **11** illustrate completely digital implementations where all of the receiver operations are performed using DSP **510**. FIGS. **12** and **13** illustrate receivers where the spatial filtering and differential measurements used for the channel estimation phase and the data communication phase are obtained using analog devices implemented in passband. In FIGS. **12** and **13**, second spatial filter operator **801** is implemented in passband; whereas in FIG. **7**, spatial filter operator **308** is implemented in baseband.

Selection between receivers **300**, **500**, **600**, **700**, **800**, **1000**, **1100**, **1200**, and **1300** depends on the system in which the receiver is being implemented. For existing MIMO systems equipped with local oscillators for downmixing the signal to baseband before analog to digital conversion, receivers **1000** and **1100** may be preferred due to the lower dimension (n vs n^2) of second spatial filter operator **801** versus spatial filter operator **308** and of quasi-coherent channel estimation operator **1002**, which reduces the computational complexity. For a receiver that has no local oscillator, third receiver **600** may be preferred over eighth receiver **1200** and ninth receiver **1300** to avoid implementation of second spatial filter operator **801** in passband, which may offset the increased computational complexity of third receiver **600**.

The word "illustrative" is used herein to mean serving as an example, instance, or illustration. Any aspect or design described herein as "illustrative" is not necessarily to be construed as preferred or advantageous over other aspects or designs. Further, for the purposes of this disclosure and unless otherwise specified, "a" or "an" means "one or more". Still further, in the detailed description, using "and" or "or" is intended to include "and/or" unless specifically indicated otherwise.

The foregoing description of illustrative embodiments of the disclosed subject matter has been presented for purposes of illustration and of description. It is not intended to be exhaustive or to limit the disclosed subject matter to the precise form disclosed, and modifications and variations are possible in light of the above teachings or may be acquired from practice of the disclosed subject matter. The embodiments were chosen and described in order to explain the principles of the disclosed subject matter and as practical applications of the disclosed subject matter to enable one skilled in the art to utilize the disclosed subject matter in various embodiments and with various modifications as suited to the particular use contemplated.

What is claimed is:

1. A non-transitory computer-readable medium having stored thereon computer-readable instructions that when executed by a computing device cause the computing device to:

spatially filter a first signal using a spatial filter matrix to define a first filtered signal, wherein the first signal is a result of a first transmitted signal transmitted by a first plurality of antennas and received by a second plurality of antennas connected to the receiver;

compute a conjugate of the first filtered signal to define a conjugate first signal;

spatially filter a second signal using the spatial filter matrix to define a second filtered signal, wherein the second signal is a result of a second transmitted signal transmitted by the first plurality of antennas and received by the second plurality of antennas connected to the receiver, wherein the second signal is received after the first signal;

compute a Hadamard product of the first filtered signal and the conjugate first signal to define a differential measurement signal; and

detect a plurality of information symbols from the differential measurement signal.

2. The non-transitory computer-readable medium of claim **1**, wherein the spatial filter matrix is computed from an estimated channel matrix.

3. The non-transitory computer-readable medium of claim **2**, wherein the estimated channel matrix is computed by transmitting a plurality of pairs of training signals before the first signal is received.

4. The non-transitory computer-readable medium of claim **3**, wherein the computer-readable instructions further cause the computing device to:

for each pair of training signals of the plurality of pairs of training signals,

compute a conjugate of a first received signal of the pair of training signals to define a conjugate first received training signal; and

compute a Kronecker product of the conjugate first received training signal and a second received signal of the pair of training signals to define a differential measurement signal for the pair of training signals;

compute a first estimated channel matrix from the defined differential measurement signal computed for each pair of training signals of the plurality of pairs of training signals; and

compute a second estimated channel matrix from the first estimated channel matrix;

wherein the spatial filter matrix is computed from the second estimated channel matrix.

5. The non-transitory computer-readable medium of claim **4**, wherein each pair of the plurality of pairs of training signals is selected so that a single column of the first estimated channel matrix is estimated from the defined differential measurement signal for the associated pair.

6. The non-transitory computer-readable medium of claim **4**, wherein the spatial filter matrix is computed using $H_o^H(\rho H_o H_o^H+\sigma^2 I_n)^{-1}$, where H_o is the second estimated channel matrix, H_o^H is a hermitian matrix computed from H_o, ρ is an estimated value of a signal to noise ratio of the plurality of pairs of training signals, σ^2 is an estimated noise power matrix computed from the plurality of pairs of training signals, and I_n is an identity matrix.

7. The non-transitory computer-readable medium of claim **4**, wherein computing the first estimated channel matrix comprises solving $z=H_d x$, where H_d is the first estimated channel matrix, $z=\text{vec}(rr_T^H)$, $x=\text{vec}(ss_T^H)$, where r is the second received signal of the pair of training signals, r_T^H is a hermitian transpose of the first received signal of the pair of training signals, where s is a second transmitted signal of the pair of training signals, and s_T^H is a hermitian transpose of a first transmitted signal of the pair of training signals.

8. The non-transitory computer-readable medium of claim **7**, wherein computing the second estimated channel matrix comprises:

define a column matrix index as one;

define a row matrix index as one;

define a second column matrix index as one;

define a number of antennas as a number of the second plurality of antennas;

(a) select n column elements from $H_d(r_i, c_1)$, where n is the number of antennas, c_1 is the column matrix index, and $r_i=r, \ldots, r+n-1$, where r is the row matrix index;

(b) select a column value from $H_d(c_1, c_1)$;

(c) normalize each of the selected n column elements using a square root of the selected column value;

(d) store the normalized n column elements in $H_o(r_j, c_2)$, where H_o is the second estimated channel matrix, c_2 is the second column matrix index, and $r_j=1, \ldots, n$;

(e) increment the row matrix index using $r=r+n$;

(f) increment the column matrix index using $c_1=c_1+n+1$;

(g) increment the second column matrix index using $c_2=c_2+1$; and

(h) repeat (a) to (g) until the second column matrix index is greater than the number of antennas.

9. A receiver comprising:

a processor; and

a non-transitory computer-readable medium operably coupled to the processor, the computer-readable medium having computer-readable instructions stored thereon that, when executed by the processor, cause the receiver to

spatially filter a first signal using a spatial filter matrix to define a first filtered signal, wherein the first signal is a result of a first transmitted signal transmitted by a first plurality of antennas and received by a second plurality of antennas connected to the receiver;

compute a conjugate of the first filtered signal to define a conjugate first signal;

spatially filter a second signal using the spatial filter matrix to define a second filtered signal, wherein the second signal is a result of a second transmitted signal transmitted by the first plurality of antennas and received by the second plurality of antennas connected to the receiver, wherein the second signal is received after the first signal;

compute a Hadamard product of the first filtered signal and the conjugate first signal to define a differential measurement signal; and

detect a plurality of information symbols from the differential measurement signal.

10. The receiver of claim 9, wherein the spatial filter matrix is computed from an estimated channel matrix.

11. The receiver of claim 10, wherein the estimated channel matrix is computed by transmitting a plurality of pairs of training signals before the first signal is received.

12. The receiver of claim 11, wherein the computer-readable instructions further cause the receiver to:

for each pair of training signals of the plurality of pairs of training signals,

compute a conjugate of a first received signal of the pair of training signals to define a conjugate first received training signal; and

compute a Kronecker product of the conjugate first received training signal and a second received signal of the pair of training signals to define a differential measurement signal for the pair of training signals;

compute a first estimated channel matrix from the defined differential measurement signal computed for each pair of training signals of the plurality of pairs of training signals; and

compute a second estimated channel matrix from the first estimated channel matrix;

wherein the spatial filter matrix is computed from the second estimated channel matrix.

13. The receiver of claim 12, wherein each pair of the plurality of pairs of training signals is selected so that a single column of the first estimated channel matrix is estimated from the defined differential measurement signal for the associated pair.

14. The receiver of claim 12, wherein the spatial filter matrix is computed using $H_o^H(\rho H_o^H{}_o^H+\sigma^2 I_n)^{-1}$, where H_o is the second estimated channel matrix, H_o^H is a hermitian matrix computed from H_o, ρ is an estimated value of a signal to noise ratio of the plurality of pairs of training signals, σ^2 is an estimated noise power matrix computed from the plurality of pairs of training signals, and I_n is an identity matrix.

15. The receiver of claim 12, wherein computing the first estimated channel matrix comprises solving $z=H_d x$, where H_d is the first estimated channel matrix, $z=\mathrm{vec}(rr_T^H)$, $x=\mathrm{vec}(ss_T^H)$, where r is the second received signal of the pair of training signals, r_T^H is a hermitian transpose of the first received signal of the pair of training signals, where s is a second transmitted signal of the pair of training signals, and s_T^H is a hermitian transpose of a first transmitted signal of the pair of training signals.

16. The receiver of claim 15, wherein computing the second estimated channel matrix comprises:

define a column matrix index as one;

define a row matrix index as one;

define a second column matrix index as one;

define a number of antennas as a number of the second plurality of antennas;

(a) select n column elements from $H_d(r_i, c_1)$, where n is the number of antennas, c_1 is the column matrix index, and $r_i=r, \ldots, r+n-1$, where r is the row matrix index;

(b) select a column value from $H_d(c_1, c_1)$;

(c) normalize each of the selected n column elements using a square root of the selected column value;

(d) store the normalized n column elements in $H_o(r_j, c_2)$, where H_o is the second estimated channel matrix, c_2 is the second column matrix index, and $r_j=1, \ldots, n$;

(e) increment the row matrix index using $r=r+n$;

(f) increment the column matrix index using $c_1=c_1+n+1$;

(g) increment the second column matrix index using $c_2=c_2+1$; and

(h) repeat (a) to (g) until the second column matrix index is greater than the number of antennas.

17. A method of detecting a plurality of information symbols, the method comprising:

spatially filtering, by a receiver, a first signal using a spatial filter matrix to define a first filtered signal, wherein the first signal is a result of a first transmitted signal transmitted by a first plurality of antennas and received by a second plurality of antennas connected to the receiver;

computing, by the receiver, a conjugate of the first filtered signal to define a conjugate first signal;

spatially filtering, by the receiver, a second signal using the spatial filter matrix to define a second filtered signal, wherein the second signal is a result of a second transmitted signal transmitted by the first plurality of antennas and received by the second plurality of antennas connected to the receiver, wherein the second signal is received after the first signal;

computing, by the receiver, a Hadamard product of the first filtered signal and the conjugate first signal to define a differential measurement signal; and

detecting, by the receiver, a plurality of information symbols from the differential measurement signal.

18. The method of claim 17, wherein the spatial filter matrix is computed from an estimated channel matrix.

19. The method of claim 18, wherein the estimated channel matrix is computed by transmitting a plurality of pairs of training signals before the first signal is received.

20. The method of claim 19, further comprising:

for each pair of training signals of the plurality of pairs of training signals,

computing, by the receiver, a conjugate of a first received signal of the pair of training signals to define a conjugate first received training signal; and

computing, by the receiver, a Kronecker product of the conjugate first received training signal and a second received signal of the pair of training signals to define a differential measurement signal for the pair of training signals;

computing, by the receiver, a first estimated channel matrix from the defined differential measurement signal computed for each pair of training signals of the plurality of pairs of training signals; and

computing, by the receiver, a second estimated channel matrix from the first estimated channel matrix;

wherein the spatial filter matrix is computed from the second estimated channel matrix.

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