



(51) International Patent Classification:

H04W 24/06 (2009.01) *H04J* 99/00 (2009.01)
H04B 7/10 (2006.01) *H04W* 16/28 (2009.01)

(21) International Application Number:

PCT/JP2014/070285

(22) International Filing Date:

24 July 2014 (24.07.2014)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

2013902848 31 July 2013 (31.07.2013)

AU

(71) Applicant: NEC CORPORATION [JP/JP]; 7-1, Shiba 5-chome, Minato-ku, Tokyo, 1088001 (JP).

(72) Inventor: SIVAHUMARAN, Thirukkumaran; c/o NEC Australia Pty. Ltd., 649-655 Springvale Road, Mulgrave, Victoria, 3170 (AU).

(74) Agent: IEIRI, Takeshi; HIBIKI IP Law Firm, Asahi Bldg. 10th Floor, 3-33-8, Tsuruya-cho, Kanagawa-ku, Yokohama-shi, Kanagawa, 2210835 (JP).

(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, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, 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, 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.

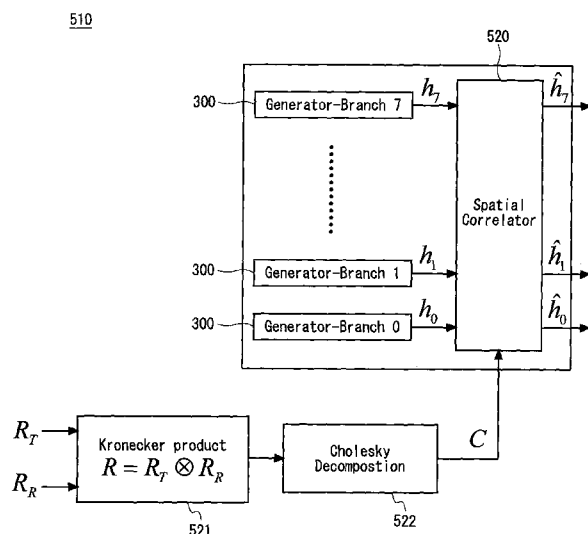
(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, 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))

(54) Title: A COMPUTER IMPLEMENTED SIMULATOR AND METHOD

Fig. 5B



(57) Abstract: A computer implemented simulator is operable to determine a first correlation matrix (R) simulating transmission path correlation between a base station and user equipment antennas. The first correlation matrix (R) is determined for simulated wireless transmission paths of a plurality of antennas having the same polarization and arranged in a two-dimensional array. The simulator is configured to: determine second correlation matrices (R_k') for a subset of the antennas which form a first side of the array, determine third correlation matrices (R_k'') for a subset of the antennas which form a second side of the array, determine fourth correlation matrices (R_k), each fourth correlation matrix being determined based on a Kronecker product of each second correlation matrix (R_k') and a corresponding third correlation matrix (R_k''), and determine the first correlation matrix (R) simulating transmission path correlation by determining a weighted sum of the one or more fourth correlation matrices (R_k).

DESCRIPTION**Title of Invention**

A COMPUTER IMPLEMENTED SIMULATOR AND METHOD

5

Technical Field

[0001]

The present invention relates to a computer implemented simulator and a method for simulating transmission path correlation between a base station and user equipment antennas.

10 More particularly, embodiments of the invention are directed to simulating mobile radio channels for evaluating, verifying, and validating radio access technologies, features, functionality and performance of wireless communication systems and equipment in relation to three dimensional beamforming and full dimensional multiple input multiple output (MIMO) technology, although the scope of the invention is not necessarily limited thereto.

15

Background Art

[0002]

MIMO enhancements in the third Generation Partnership Project (3GPP) Long Term Evolution (LTE) including Rel-11 were designed taking into account antenna configurations at
20 the base station, such as LTE enhanced base station node (eNodeB), that are capable of adaptation in only one plane, for example the horizontal plane.

[0003]

Recently, antenna systems having a two-dimensional array structure have been studied by 3GPP RAN-WG1 as a potential option for enhancing system performance NPL1, NPL2 and
25 NPL3.

[0004]

A two-dimensional antenna array enables adaptive control over an additional plane, for example, thus the vertical plane, enabling different strategies such as adaptation of a vertical beam pattern and/or tilt, vertical sectorization and user-specific elevation beamforming.

30

Citation List**Non Patent Literature**

[0005]

NPL 1: ARTIST 4G, WP1, "D1.2 - Innovative advanced signal processing algorithms

for interference avoidance”, v1.0 31/12/2010

NPL 2: 3GPP RP-121994, “Study on Downlink Enhancements for Elevation Beamforming for LTE”

NPL 3: 3GPP RP122015, “Study on Full Dimension MIMO for LTE”

5 **NPL 4:** 3GPP TS 36.101, “User Equipment (UE) radio transmission and reception (Release 11)”, v11.3.0 (2012-12)

NPL 5: Paul D. Teal, Thushara D. Abhayapala, “Spatial Correlation for General Distributions of Scatterers”, IEEE Signal Processing Letters, Vol 9, Issue 10, Oct 2002, pp305-307

10 **NPL 6:** Su Khiong Yong, John S. Thompson, “Three-Dimensional Spatial Fading Correlation Models for Compact MIMO Receivers”, IEEE Trans on Wireless Comm, Vol14, Issue6, Nov2005, pp2856-2868

NPL 7: 3GPP TR 25.996, “Spatial channel model for Multiple Input Multiple Output (MIMO) simulations (Release 11)”, v11.0.0 (2012-09)

15

Summary of Invention

Technical Problem

[0006]

To verify the performance of these new technologies by a modelling simulation, it is
20 necessary to emulate the mobile radio channels taking into account radio frequency propagation constructed by the two-dimensional antenna arrangement/configuration into a three-dimensional scattering environment.

[0007]

Embodiments of the present invention provide a simulator and method for simulating
25 transmission path correlation between base station and user equipment antennas with sufficient accuracy, as well as computational and memory efficiency.

[0008]

It will be clearly understood that, if a prior art publication is referred to herein, this reference does not constitute an admission that the publication forms part of the common general
30 knowledge in the art in Australia or in any other country.

Solution to Problem

[0009]

According to one aspect of the invention, a computer implemented simulator operable to

determine a first correlation matrix (R) simulating transmission path correlation between a base station and user equipment antennas is provided, the first correlation matrix (R) being determined for simulated wireless transmission paths of a plurality of antennas having the same polarization and arranged in a two-dimensional array, the computer implemented simulator being
 5 configured to:

determine one or more second correlation matrices (R_k') for a subset of the antennas which form a first side of the array,

determine one or more third correlation matrices (R_k'') for a subset of the antennas which form a second side of the array,

10 determine one or more fourth correlation matrices (R_k), each fourth correlation matrix being determined based on a Kronecker product ($R_k = R_k' \otimes R_k''$) of each second correlation matrix (R_k') and a corresponding third correlation matrix (R_k''),

and

determine the first correlation matrix (R) simulating transmission path correlation by
 15 determining a weighted sum of the one or more fourth correlation matrices (R_k).

[0010]

Advantageously, by using the Kronecker product of the third and fourth correlation matrices (R_k' , R_k'') and the weighted sum of the fourth correlation matrices (R_k), the first correlation matrix (R) can be determined with sufficient accuracy and relatively low

20 computational complexity, thereby achieving computational and memory efficiency. This is particularly important in the event that the number of antennas is high.

[0011]

The array may be rectangular. In addition, the second side may be adjacent the first side. Moreover, the computer implemented simulator may be configured to:

25 determine a number of sets (K) for grouping the simulated wireless transmission paths, determine weight factors associated with the one or more sets (K), and determine the weighted sum of the one or more fourth correlation matrices (R_k) using the weight factors.

[0012]

30 The computer implemented simulator may be configured to:

divide a three-dimensional transmission space of the transmission paths into a number of sectors equal to the number of sets (K), each sector being defined by an elevation angle range (θ) and an azimuth angle range (ϕ), and

group the transmission paths which have an elevation angle (θ) and an azimuth angle

(φ) falling within the same sector so as to form K sets of transmission paths.

[0013]

The computer implemented simulator may be configured to determine the one or more second correlation matrices (R_k) by determining a second correlation matrix

$$5 \quad R'_k = \begin{bmatrix} r'_{0,0} & r'_{0,1} & \dots & r'_{0,j} \\ r'_{1,0} & r'_{1,1} & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r'_{i,0} & \dots & \dots & r'_{i,j} \end{bmatrix} \text{ for each set } (k) \text{ of transmission paths using the following equation:}$$

$$r'_{i,j} = \frac{1}{Q_k} \sum_{m=1}^{M_k} G(\theta_m, \varphi_m) \exp(j2\pi d'_{i,j} \cos \theta_m \sin \phi_m)$$

$$Q_k = \sum_{m=1}^{M_k} G(\theta_m, \varphi_m)$$

wherein $d'_{i,j}$ is a normalized distance with respect to a wavelength (λ) of a carrier between two antennas (i, j) along the first side of the two-dimensional array, θ_m is an angle that a sub-path (m) extends to a reference plane formed by the first side of the two-dimensional array and a direction perpendicular to the array, φ_m is an angle between the projection of the sub-path (m) on the reference plane and the direction perpendicular to the array, and M_k is the number of transmission paths in a set (k).

[0014]

The computer implemented simulator may be configured to determine the one or more second correlation matrices (R_k) by determining a second correlation matrix

$$15 \quad R'_k = \begin{bmatrix} r'_{0,0} & r'_{0,1} & \dots & r'_{0,j} \\ r'_{1,0} & r'_{1,1} & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r'_{i,0} & \dots & \dots & r'_{i,j} \end{bmatrix} \text{ for each set } (k) \text{ of transmission paths using the following equation:}$$

$$r'_{i,j} = \frac{1}{Q_k} \int \int_{\theta_k \phi_k} P(\theta, \varphi) G(\theta, \varphi) \exp(j2\pi d'_{i,j} \cos \theta \sin \phi) d\phi d\theta$$

$$Q_k = \int \int_{\theta_k \phi_k} P(\theta, \varphi) G(\theta, \varphi) d\phi d\theta$$

wherein $d'_{i,j}$ is a normalized distance with respect to a wavelength (λ) of a carrier between two antennas (i, j) along the first side of the two-dimensional array, θ is an elevation angle above a reference plane formed by the first side of the two-dimensional array and a direction perpendicular to the array, φ is an angle measured from a direction perpendicular to

the array on the reference plane, and a domain of integration θ_k, ϕ_k correspond to set k .

[0015]

The computer implemented simulator may be configured to determine the second

correlation matrix $\mathbf{R}'_k = \begin{bmatrix} r'_{0,0} & r'_{0,1} & \dots & r'_{0,j} \\ r'_{1,0} & r'_{1,1} & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r'_{i,0} & \dots & \dots & r'_{i,j} \end{bmatrix}$ using the following equation:

$$r'_{i,j} = \alpha' \left[\frac{i-j}{N'-1} \right]^2$$

wherein N' is the number of antennas along the first side of the array, and parameter α' is defined based on a required Ergodic capacity expectation.

[0016]

The computer implemented simulator may be configured to determine the one or more
10 third correlation matrices ($\mathbf{R}_k''$) by determining a third correlation matrix

$\mathbf{R}_k'' = \begin{bmatrix} r''_{0,0} & r''_{0,1} & \dots & r''_{0,j} \\ r''_{1,0} & r''_{1,1} & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r''_{i,0} & \dots & \dots & r''_{i,j} \end{bmatrix}$ for each set (k) of transmission paths using the following equation:

$$r''_{i,j} = \frac{1}{Q_k} \sum_{m=1}^{M_k} G(\theta_m, \varphi_m) \exp(j2\pi d''_{i,j} \sin \theta_m)$$

$$Q_k = \sum_{m=1}^{M_k} G(\theta_m, \varphi_m)$$

wherein $d''_{i,j}$ is a normalized distance with respect to a wavelength (λ) of a carrier
between two antennas (i, j) along the second side of the two-dimensional array, θ_m is an angle
15 that sub-path (m) extends to a reference plane formed by the first side of the two-dimensional
array and a direction perpendicular to the array, φ_m is an angle between the projection of the
sub-path (m) on the reference plane and the direction perpendicular to the array, and M_k is the
number of transmission paths in a set (k).

[0017]

20 The computer implemented simulator may be configured to determine the one or more
third correlation matrices ($\mathbf{R}_k''$) by determining a third correlation matrix

$$\mathbf{R}_k'' = \begin{bmatrix} r_{0,0}'' & r_{0,1}'' & \dots & r_{0,j}'' \\ r_{1,0}'' & r_{1,1}'' & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r_{i,0}'' & \dots & \dots & r_{i,j}'' \end{bmatrix} \text{ for each set } (k) \text{ of transmission paths using the following equation:}$$

$$r_{i,j}'' = \frac{1}{Q_k} \int \int_{\theta_k \phi_k} P(\theta, \varphi) G(\theta, \varphi) \exp(j2\pi d_{i,j}'' \sin \theta) d\phi d\theta$$

$$Q_k = \int \int_{\theta_k \phi_k} P(\theta, \varphi) G(\theta, \varphi) d\phi d\theta$$

wherein $d_{i,j}''$ is the normalized distance with respect to a wavelength (λ) of a carrier

5 between two antennas (i, j) along the second side of the two-dimensional array, θ is an elevation angle above a reference plane formed by the first side of the two-dimensional array and a direction perpendicular to the array, φ is an angle measured from the direction perpendicular to the array on the reference plane, and a domain of integration θ_k, ϕ_k correspond to set k .

[0018]

10 The computer implemented simulator may be configured to determine a third

correlation matrix $\mathbf{R}_k'' = \begin{bmatrix} r_{0,0}'' & r_{0,1}'' & \dots & r_{0,j}'' \\ r_{1,0}'' & r_{1,1}'' & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r_{i,0}'' & \dots & \dots & r_{i,j}'' \end{bmatrix}$ using the following equation:

$$r_{i,j}'' = \alpha'' \left[\frac{i-j}{N''-1} \right]^2$$

wherein N'' is the number of antennas along the second side of the array, and parameter α'' is defined based on a required Ergodic capacity expectation.

15 [0019]

The computer implemented simulator may be further operable to determine spatially correlated coefficients for the simulated wireless transmission paths by being configured to:

obtain a matrix square root of a receive correlation matrix,

$$\mathbf{R}_R = \mathbf{C}_R \mathbf{C}_R^H$$

20 obtain a matrix square root of a transmit correlation matrix along direction 1,

$$\mathbf{R}' = \mathbf{C}' \mathbf{C}'^H$$

obtain a matrix square root of a transmit correlation matrix along direction 2,

$$\mathbf{R}'' = \mathbf{C}'' \mathbf{C}''^H$$

determine receiver correlation for each transmit antenna:

$$\bar{H}_{i,j,l} = C_R H_{i,j,l} \quad \forall j, l$$

determine transmit correlation along direction 1 for each transmit antenna along direction 2 and receive antenna

$$\tilde{H}_{i,j,l} = C'_0 \bar{H}_{i,j,l} \quad \forall i, l$$

- 5 determine transmit correlation along direction 2 for each transmit antenna along direction 1 and receive antenna

$$\hat{H}_{i,j,l} = C''_0 \tilde{H}_{i,j,l} \quad \forall i, j$$

wherein $H_{i,j,l}$ denotes uncorrelated input coefficients between a receive antenna i , a transmit antenna given by index j along direction 1, and a transmit antenna given by index l along direction 2.

[0020]

The computer implemented simulator may be further operable to determine a spatial correlation matrix ($\mathbf{R}_{\text{spatial}}$) for facilitating the designing, evaluating and testing of three-dimensional beamforming, FD-MIMO algorithms in which a rectangular antenna array is used at a base station node and a linear antenna array is used at a user equipment, the spatial correlation matrix being determined based on the following Kronecker product formula:

$$\mathbf{R}_{\text{spatial}} = \mathbf{R}'_{eNB} \otimes \mathbf{R}''_{eNB} \otimes \mathbf{R}_{UE}$$

wherein

$\mathbf{R}'_{eNB}$ is a correlation matrix of the rectangular antenna array at the base station node, and elements of matrix $\mathbf{R}'_{eNB}$ can be determined using a formula $r'_{i,j} = \alpha' \left[\frac{i-j}{N'-1} \right]^2$,

$\mathbf{R}''_{eNB}$ is a further correlation matrix of the rectangular antenna array at the base station node, and elements of matrix $\mathbf{R}''_{eNB}$ can be determined using a formula $r''_{i,j} = \alpha'' \left[\frac{i-j}{N''-1} \right]^2$,

$\mathbf{R}_{UE}$ is a correlation matrix of the linear antenna array at the user equipment, and elements of matrix $\mathbf{R}_{UE}$ can be determined using a formula: $r_{i,j} = \beta \left[\frac{i-j}{N-1} \right]^2$,

25 N' , N'' are the numbers of antennas at the base station node along two adjacent sides of the rectangular antenna array respectively,

N is the number of antennas at the user equipment, and

values for α' , α'' and β for different correlation levels are selected from the following table 1:

[table 1]

Correlation levels	α'	α''	β
Low	0	0	0
Medium	0.3	0.3	0.9
High	0.9	0.9	0.9

[0021]

According to another aspect of the invention, a method for determining a first correlation matrix (R) simulating transmission path correlation between a base station and user equipment antennas is provided, the first correlation matrix (R) being determined for simulated wireless transmission paths of a plurality of antennas having the same polarization and arranged in a two-dimensional array, the method including the steps of:

determining one or more second correlation matrices (R_k') for a subset of the antennas which form a first side of the array,

determining one or more third correlation matrices (R_k'') for a subset of the antennas which form a second side of the array adjacent the first side,

determining one or more fourth correlation matrices (R_k), each fourth correlation matrix being determined based on a Kronecker product ($R_k = R_k' \otimes R_k''$) of each second correlation matrix (R_k') and a corresponding third correlation matrix (R_k''), and

determining the first correlation matrix (R) simulating transmission path correlation by determining a weighted sum of the one or more fourth correlation matrices (R_k).

[0022]

The method may include:

determining a number of sets (K) for grouping the simulated wireless transmission paths,

determining weight factors associated with the one or more sets (K), and

determining the weighted sum of the one or more fourth correlation matrices (R_k) using the weight factors.

[0023]

The method may include:

dividing a three-dimensional transmission space of the transmission paths into a number of sectors equal to the number of sets (K), each sector being defined by an elevation angle range (θ) and an azimuth angle range (ϕ), and

grouping the transmission paths which have an elevation angle (θ) and an azimuth angle (φ) falling within the same sector so as to form K sets of transmission paths.

[0024]

The method may include:

- 5 determining the one or more second correlation matrices (R'_k) by determining a second

correlation matrix $R'_k = \begin{bmatrix} r'_{0,0} & r'_{0,1} & \dots & r'_{0,j} \\ r'_{1,0} & r'_{1,1} & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r'_{i,0} & \dots & \dots & r'_{i,j} \end{bmatrix}$ for each set (k) of transmission paths using the

following equation:

$$r'_{i,j} = \frac{1}{Q_k} \sum_{m=1}^{M_k} G(\theta_m, \varphi_m) \exp(j2\pi d'_{i,j} \cos \theta_m \sin \phi_m)$$

$$Q_k = \sum_{m=1}^{M_k} G(\theta_m, \varphi_m)$$

- 10 wherein $d'_{i,j}$ is a normalized distance with respect to a wavelength (λ) of a carrier between two antennas (i, j) along the first side of the two-dimensional array, θ_m is an angle that a sub-path (m) extends to a reference plane formed by the first side of the two-dimensional array and a direction perpendicular to the array, φ_m is an angle between the projection of the sub-path (m) on the reference plane and the direction perpendicular to the array, and M_k is the number of transmission paths in a set (k).

15 [0025]

The method may include:

- determining the one or more second correlation matrices (R'_k) by determining a second

correlation matrix $R'_k = \begin{bmatrix} r'_{0,0} & r'_{0,1} & \dots & r'_{0,j} \\ r'_{1,0} & r'_{1,1} & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r'_{i,0} & \dots & \dots & r'_{i,j} \end{bmatrix}$ for each set (k) of transmission paths using the

following equation:

20
$$r'_{i,j} = \frac{1}{Q_k} \iint_{\theta_k \phi_k} P(\theta, \varphi) G(\theta, \varphi) \exp(j2\pi d'_{i,j} \cos \theta \sin \phi) d\phi d\theta$$

$$Q_k = \iint_{\theta_k \phi_k} P(\theta, \varphi) G(\theta, \varphi) d\phi d\theta$$

wherein $d'_{i,j}$ is the normalized distance with respect to a wavelength (λ) of a carrier

between two antennas (i, j) along the first side of the two-dimensional array, θ is an elevation angle above a reference plane formed by the first side of the two-dimensional array and a direction perpendicular to the array, ϕ is an angle measured from the direction perpendicular to the array on the reference plane, and a domain of integration θ_k, ϕ_k correspond to set k .

5 [0026]

The method may include determining a second correlation matrix

$$\mathbf{R}'_k = \begin{bmatrix} r'_{0,0} & r'_{0,1} & \dots & r'_{0,j} \\ r'_{1,0} & r'_{1,1} & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r'_{i,0} & \dots & \dots & r'_{i,j} \end{bmatrix} \text{ using the following equation:}$$

$$r'_{i,j} = \alpha' \left[\frac{i-j}{N'-1} \right]^2$$

10 wherein N' is the number of antenna along the first side of the array, and parameter α' is defined based on a required Ergodic capacity expectation.

[0027]

The method may include determining the one or more third correlation matrices ($\mathbf{R}_k''$)

$$\text{by determining a third correlation matrix } \mathbf{R}_k'' = \begin{bmatrix} r''_{0,0} & r''_{0,1} & \dots & r''_{0,j} \\ r''_{1,0} & r''_{1,1} & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r''_{i,0} & \dots & \dots & r''_{i,j} \end{bmatrix} \text{ for each set } (k) \text{ of}$$

transmission paths using the following equation:

$$15 \quad r''_{i,j} = \frac{1}{Q_k} \sum_{m=1}^{M_k} G(\theta_m, \phi_m) \exp(j2\pi d''_{i,j} \sin \theta_m)$$

$$Q_k = \sum_{m=1}^{M_k} G(\theta_m, \phi_m)$$

20 wherein $d''_{i,j}$ is a normalized distance with respect to a wavelength (λ) of a carrier between two antennas (i, j) along the second side of the two-dimensional array, θ_m is an angle that a sub-path m extends to a reference plane formed by the first side of the two-dimensional array and a direction perpendicular to the array, ϕ_m is an angle between the projection of the sub-path (m) on the reference plane and the direction perpendicular to the array, and M_k is the number of transmission paths in a set (k).

[0028]

The method may include determining the one or more third correlation matrices ($\mathbf{R}_k''$)

by determining a third correlation matrix $\mathbf{R}_k'' = \begin{bmatrix} r_{0,0}'' & r_{0,1}'' & \cdots & r_{0,j}'' \\ r_{1,0}'' & r_{1,1}'' & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ r_{i,0}'' & \cdots & \cdots & r_{i,j}'' \end{bmatrix}$ for each set (k) of

transmission paths using the following equation:

$$r_{i,j}'' = \frac{1}{Q_k} \int \int_{\theta_k \phi_k} P(\theta, \phi) G(\theta, \phi) \exp(j2\pi d_{i,j}'' \sin \theta) d\phi d\theta$$

$$Q_k = \int \int_{\theta_k \phi_k} P(\theta, \phi) G(\theta, \phi) d\phi d\theta$$

wherein $d_{i,j}''$ is a normalized distance with respect to a wavelength (λ) of a carrier between two antennas (i, j) along the second side of the two-dimensional array, θ is an elevation angle above a reference plane formed by the first side of the two-dimensional array and a direction perpendicular to the array, ϕ is an angle measured from a direction perpendicular to the array on the reference plane, and a domain of integration θ_k, ϕ_k correspond to set k .

[0029]

The method may include determining a third correlation matrix

$\mathbf{R}_k'' = \begin{bmatrix} r_{0,0}'' & r_{0,1}'' & \cdots & r_{0,j}'' \\ r_{1,0}'' & r_{1,1}'' & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ r_{i,0}'' & \cdots & \cdots & r_{i,j}'' \end{bmatrix}$ using the following equation:

$$r_{i,j}'' = \alpha'' \left[\frac{i-j}{N''-1} \right]^2$$

wherein N'' is the number of antenna along the second side of the array, and parameter α'' is defined based on a required Ergodic capacity expectation.

[0030]

The method may further include determining spatially correlated coefficients for the simulated wireless transmission paths by:

obtaining a matrix square root of a receive correlation matrix,

$$\mathbf{R}_R = \mathbf{C}_R \mathbf{C}_R^H$$

obtaining a matrix square root of a transmitting correlation matrix along direction 1,

$$\mathbf{R}' = \mathbf{C}' \mathbf{C}'^H$$

obtaining a matrix square root of a transmitting correlation matrix along direction 2,

$$\mathbf{R}'' = \mathbf{C}'' \mathbf{C}''^H$$

determining receiver correlation for each transmit antenna using the following formula:

$$\bar{H}_{i,j,l} = \mathbf{C}_R H_{i,j,l} \quad \forall j, l$$

determining transmit correlation along direction 1 for each transmit antenna along
5 direction 2 and receive antenna using the following formula:

$$\tilde{H}_{i,j,l} = \mathbf{C}'_0 \bar{H}_{i,j,l} \quad \forall i, l$$

determining transmit correlation along direction 2 for each transmit antenna along
direction 1 and receive antenna using the following formula:

$$\hat{H}_{i,j,l} = \mathbf{C}''_0 \tilde{H}_{i,j,l} \quad \forall i, j$$

10 wherein $H_{i,j,l}$ denotes uncorrelated input coefficients between a receive antenna i , a transmit antenna given by index j along direction 1, and a transmit antenna given by index l along direction 2.

[0031]

The method may further include determining a spatial correlation matrix
15 ($\mathbf{R}_{\text{spatial}}$) for facilitating the designing, evaluating and testing of three-dimensional beamforming, FD-MIMO algorithms in which a rectangular antenna array is used at a base station node and a linear antenna array is used at a user equipment, the spatial correlation matrix being determined based on the following Kronecker product formula:

$$\mathbf{R}_{\text{spatial}} = \mathbf{R}'_{eNB} \otimes \mathbf{R}''_{eNB} \otimes \mathbf{R}_{UE}$$

20 wherein

$\mathbf{R}'_{eNB}$ is a correlation matrix of the rectangular antenna array at the base station

node, and elements of matrix $\mathbf{R}'_{eNB}$ can be determined using the formula: $r'_{i,j} = \alpha' \left[\frac{i-j}{N'-1} \right]^2$,

$\mathbf{R}''_{eNB}$ is a further correlation matrix of the rectangular antenna array at the base

station node, and elements of matrix $\mathbf{R}''_{eNB}$ can be determined using the formula: $r''_{i,j} = \alpha'' \left[\frac{i-j}{N''-1} \right]^2$,

25 $\mathbf{R}_{UE}$ is a correlation matrix of the linear antenna array at the user equipment,

and elements of matrix $\mathbf{R}_{UE}$ can be determined using the formula: $r_{i,j} = \beta \left[\frac{i-j}{N-1} \right]^2$,

N' , N'' are the numbers of antennas at the base station node along two adjacent sides of the rectangular antenna array,

N is the number of antennas at the user equipment, and values for α' , α'' and β for different correlation levels are selected from the following table 2:

[table 2]

Correlation levels	α'	α''	β
Low	0	0	0
Medium	0.3	0.3	0.9
High	0.9	0.9	0.9

[0032]

In one embodiment, the invention provides a method for generating a set of correlation matrices defining the correlation between the advanced base station antennas such as eNodeB and advanced user equipment antennas in the case of three dimensional multi-antenna systems supporting baseband implemented 3D beamforming and full dimension MIMO techniques. The set of correlation matrices defining the correlation between the advanced base station antennas such as eNodeB and advanced user equipment antennas generated may be standardized to be realized by computerised simulation in designing, evaluating and validating features/functions related to 3D-beam forming and/or full dimensional MIMO. Moreover, the set of correlation matrices defining the correlation between the advanced base station antennas such as eNodeB and advanced user equipment antennas generated may be further realized for being implemented as an apparatus in a laboratory validating advanced base station and user equipment supporting 3D beamforming and full dimension MIMO techniques.

[0033]

According to the embodiment, the method generates a transmit and/or receive correlation matrix for multiple transmit and/or receive antennas arranged in rectangular array. A computationally and memory efficient system that can be used to obtain spatially correlated coefficients when the correlation matrix is obtained is also provided.

[0034]

The method may include first obtaining the correlation matrices for two linear antenna arrays forming either side of the rectangular array, and then performing a Kronecker product to obtain the correlation matrix of the rectangular array of antennas.

[0035]

The method may include obtaining the correlation matrix of the rectangular array of antennas as the sum of correlation matrices, wherein each correlation matrix is formed while

considering only a sub-set of non-overlapping scatterers.

[0036]

The generated transmit and/or receive correlation matrix may be used to generate a spatial correlation matrix of a MIMO channel for the emulation of MIMO wireless channel.

5 [0037]

Advantageously, embodiments of the invention provide a method for establishing a control environment such as computerized simulation for designing, evaluating and validating Active antenna system technologies including 3D beam forming and Full Dimensional MIMO.

[0038]

10 More particularly, embodiments of the present invention enable sufficiently accurate emulation of MIMO wireless channels to evaluate new technologies such as elevation beamforming and FD-MIMO. The method can advantageously be executed by a system in a manner that is computationally efficient for large number of antennas arranged in a rectangular array.

15 [0039]

Embodiments of the invention further provides a method to generate the transmit and/or receive correlation matrix for a rectangular antenna array that can advantageously be used for link level emulation of a MIMO wireless channel that is accurate enough for computerized evaluating and testing wireless systems/devices/algorithm that employ 3D elevation
20 beamforming and FD-MIMO technologies.

[0040]

Moreover, embodiments of the invention provides a computationally and memory efficient system that can be used to obtain spatially correlated coefficients when the correlation matrix is obtained based on the above method.

25 [0041]

Any of the features described herein can be combined in any combination with any one or more of the other features described herein within the scope of the invention.

[0042]

The reference to any prior art in this specification is not and should not be taken as an
30 acknowledgement or any form of suggestion that the prior art forms part of the common general knowledge.

Advantageous Effects of Invention

[0043]

According to the present invention, it is possible to provide a simulator and method for simulating transmission path correlation between base station and user equipment antennas with sufficient accuracy, as well as computational and memory efficiency.

5 Brief Description of Drawings

[0044]

Preferred features, embodiments and variations of the invention may be discerned from the following Detailed Description which provides sufficient information for those skilled in the art to perform the invention. The Detailed Description is not to be regarded as limiting the scope
10 of the preceding Summary of the Invention in any way. The Detailed Description will make reference to a number of drawings as follows:

[Fig. 1]

Fig. 1 is a schematic diagram illustrating wireless transmission paths between a transmitter and a receiver.

15 [Fig. 2]

Fig. 2 is a schematic diagram illustrating a tapped delay line system for emulating the transmission paths of Fig. 1.

[Fig. 3]

Fig. 3 is a schematic diagram of a tap coefficient generator for generating coefficients
20 used in the tapped delay line system of Fig. 2.

[Fig. 4]

Fig. 4 is a schematic diagram illustrating wireless transmission paths between four transmitters and two receivers in a Multiple Input Multiple Output (MIMO) channel system.

[Fig. 5]

25 Fig. 5 is a schematic diagram illustrating emulator system for emulating the transmission paths of Fig. 4.

[Fig. 6]

Fig. 6 is a schematic diagram illustrating cross-polarized antenna configurations.

[Fig. 7]

30 Fig. 7 is a schematic diagram illustrating a linear antenna array.

[Fig. 8]

Fig. 8 is a schematic diagram illustrating 3 dimensional scattering of a group of transmission paths.

[Fig. 9]

Fig. 9 is a schematic diagram illustrating a rectangular antenna array.

[Fig. 10]

Fig. 10 is a flow diagram illustrating a method for determining a first correlation matrix (R) simulating transmission path correlation between a base station and user equipment antennas according to an embodiment of the present invention.

[Fig. 11]

Fig. 11 is a schematic diagram of a system for introducing spatial correlation based on the first correlation matrix (R) determined using the method of Fig. 10. It describes the case where $K=1$.

Description of Embodiments

[0045]

The following table 3 provides an explanation of the abbreviations used in the present specification.

[table 3]

Abbreviation	Description
3D	Three Dimension
3GPP	3 rd Generation Partnership Project
AAS	Active Antenna Systems
AoA	Azimuth angle of Arrival
AoD	Azimuth angle of Departure
DL	Down Link
EoA	Elevation angle of Arrival
EoD	Elevation angle of Departure
eNB/eNodeB	Enhanced Based Station Node (NodeB)
FD-MIMO	Full Dimension – MIMO

LTE	Long Term Evolution
LTE-A	LTE Advanced
MIMO	Multiple Input Multiple Output
RF	Radio Frequency
rms	Root Mean Square
UE	User Equipment

[0046]

Traditionally, a single link of a wireless channel can be represented as illustrated in Fig.

1. A radio signal from a transmitter 121, due to the presence of various scattering objects 110, and 111 in the environment, propagates along multiple sub-paths 151-156 and reaches the receiver 131 at different delays with different phases and amplitudes. At a receiver, it is not possible to resolve the signals from the paths when they arrive with small relative delays. In Fig. 1, sub-paths 151-153 that arrive with small relative delays are clustered into one path 141 and sub-paths 154-156 that arrive with small relative delays are clustered into another path 142.

[0047]

Furthermore, the small scale (i.e. microscopic) fading of a single link of a wireless channel in a discretized time baseband can be emulated using a tapped delay line system 200 shown in Fig. 2. The taps in the tapped delay line correspond to the resolvable paths. The complex tap coefficients 221 to 224 correspond to the amplitude and phase of the signal along each resolvable path.

[0048]

Considering that each resolvable path consists of possibly many sub-paths, the tap coefficients 221-224 are generally characterized by an independent zero-mean complex valued Gaussian process.

[0049]

An exemplary system used to generate the tap coefficients 221-224 is further illustrated in Fig. 3. Each tap coefficient 221 to 224 in system 200 shown in Fig. 2 is generated by filtering the output of a complex white Gaussian noise generator 311 by a Doppler filter 321.

[0050]

The Doppler filter is introduced to take into account the variation of the tap coefficients

with time due to the transmitter or receiver mobility. The Doppler filter is generally characterized by the Jakes power spectrum.

[0051]

Smart antenna technology such as MIMO has been shown to improve the performance
5 of mobile radio systems and has been incorporated into the latest mobile standards, for example, 3rd Generation Partnership Project (3GPP) LTE/LTE-A.

[0052]

Smart antenna technology generally uses multiple antennas at the transmitter and receiver and use spatial processing to combine the signals from the multiple antennas.

10 [0053]

In order to verify the performance and functionality of this technology it is necessary to emulate the channel between each of the transmit-receive antenna pairs. This channel is normally referred to as the MIMO channel.

[0054]

15 An exemplary antenna configuration forming a MIMO channel is illustrated in Fig. 4. There are four antennas 0,1,2 and 3 at the transmitters numbered 462 to 465 arranged linearly and two antennas 0 and 1 at the receivers numbered 472, 473. The channel between a transmit-receive antenna pair is commonly referred to as a branch. For example a branch 7 representing the channel between transmit antenna 3 (465) and receive antenna 1 (473) is
20 numbered as 481.

[0055]

An exemplary system 500 to emulate the MIMO channel in example of the antenna configuration 400 is illustrated in Fig. 5. The MIMO channel is commonly emulated using multiple tapped delay lines, i.e. one tapped delay line for example, tapped delay line system 200
25 to emulate one branch, for example, branch 481. The system also consists of multiple sub-systems 510 each of which generates tap coefficients for each branch of a single tap.

[0056]

An exemplary system 510 to emulate the tap coefficients for a single tap of the MIMO channel in example of the antenna configuration 400 is illustrated in Fig. 5. It consists of
30 multiple blocks 300 for generating independent Doppler-filtered white Gaussian noise for each branch of the MIMO channel. This is followed by a spatial correlator 520 to introduce correlation between the branches.

[0057]

The spatial correlator 520 performs linear filtering on the uncorrelated input coefficients to produce correlated coefficients.

[0058]

This operation can be mathematically expressed by the following formula, correlator

$$\hat{\mathbf{h}} = \mathbf{C}\mathbf{h}$$

where $\mathbf{h}$ represents the input vector (of size 8(=4x2) in the example of the antenna configuration 400) of uncorrelated tap coefficients and $\hat{\mathbf{h}}$ represent the output vector (of size 8(=4x2) in the example of the antenna configuration 400) of correlated tap coefficients and $\mathbf{C}$ the linear filtering matrix (of size 8 by 8 in the example of the antenna configuration 400).

10 [0059]

The correlation between the tap coefficients $\hat{h}_i$ and $\hat{h}_j$ is then given by the i th row and j th column of the following matrix $\mathbf{R}$:

$$\mathbf{R} = E[\hat{\mathbf{h}}\hat{\mathbf{h}}^H] = E[\mathbf{C}\mathbf{h}\mathbf{h}^H\mathbf{C}^H] = \mathbf{C}E[\mathbf{h}\mathbf{h}^H]\mathbf{C}^H = \mathbf{C}\mathbf{C}^H$$

[0060]

15 The correlation matrix $\mathbf{R}$ for a MIMO channel is generally estimated based on antennas characteristics and the scattering environment, and then the linear filtering matrix $\mathbf{C}$ is calculated as the square root of the correlation matrix $\mathbf{R}$ using techniques such as Cholesky decomposition.

[0061]

20 For wireless fading channels, when the transmitter array is placed far away from the receiver array (as is the case of mobile systems) and when all the antennas have the same polarization (as in the example of the antenna configuration 400), it is possible to compute the correlation matrix $\mathbf{R}$ as

$$\mathbf{R} = \mathbf{R}_T \otimes \mathbf{R}_R$$

25 where $\mathbf{R}_T$ is the transmit-side correlation matrix (of size 4 by 4 in the example of the antenna configuration 400), $\mathbf{R}_R$ is the receiver-side correlation matrix (of size 2 by 2 in the example of the antenna configuration 400) and $\otimes$ is the Kronecker product (NPL4). To use the above computation for $\mathbf{R}$, the element of the input vector $\mathbf{h}$ (and consequently output vector $\hat{\mathbf{h}}$) should be arranged in the following order, i.e.

$$\mathbf{h} = [H_{0,0}, H_{1,0}, H_{0,1}, \dots, H_{1,3}]^T$$

30

where $H_{i,j}$ represents the tap coefficient between receive antenna i and transmit antenna j or in other words

$$\mathbf{h} = \text{vec}(\mathbf{H})$$

where $\mathbf{H}$ is a matrix with elements $H_{i,j}$ and operator $\text{vec}()$ represents stacking the columns of a matrix one below the other to form a vector.

[0062]

An example 600 of a cross polarized eNB antenna array and cross polarized UE antenna array is shown in Fig. 6. The eNB antenna array has four antennas 0,1,2 and 3 numbered 662-665. Antennas 0 (662) and 2 (664) have $+45^\circ$ polarization while antennas 1 (663) and 3 (665) have -45° polarization. The UE antenna array has two antennas 0 and 1 numbered 672 and 673. Antenna 0 (672) has horizontal polarization while antenna 1 (673) has vertical polarization.

[0063]

In the DL, when the cross polarized eNB antenna array is used for transmission and the cross polarized UE antenna array is used for reception, the correlation matrix $\mathbf{R}$ can be computed as

$$\mathbf{R} = \mathbf{R}_T \otimes \mathbf{\Gamma} \otimes \mathbf{R}_R$$

where $\mathbf{R}_T$ is the transmit-side correlation matrix for the sub-array of a transmit antenna with the same polarization (of size 2 by 2 for the example in 600), $\mathbf{R}_R$ is the receiver-side correlation matrix for the sub-array of transmit antennas with the same polarization (of size 1 by 1 for the example in 600), $\mathbf{\Gamma}$ is the polarization correlation between the different polarizations (of size 4 by 4 for the example in 600) and $\otimes$ is the Kronecker product (NPL4). Please note that to use the above computation for $\mathbf{R}$, the element of the input vector $\mathbf{h}$ (and consequently output vector $\hat{\mathbf{h}}$) should be arranged appropriately.

[0064]

The transmit-side correlation matrix for an array of transmit antenna with the same polarization is estimated based on the transmit antenna characteristics and the scattering environment around the transmitter. The receiver-side correlation matrix is estimated based on the receive antenna characteristics and the scattering environment around the receiver.

[0065]

Fig. 7 illustrates an array of four transmit antennas 0,1,2 and 3 numbered 751 to 754 for example on an eNB of a cellular system equally spaced along the axis 730.

[0066]

Fig. 8 illustrates the multiple sub-paths of path 810 corresponding to a tap for which the transmit-side correlation matrix $\mathbf{R}_T$ or receive side correlation matrix is estimated $\mathbf{R}_R$.

[0067]

Path 810 has many sub-paths M . The direction of a sub-path m for example 820, can be specified with reference to the co-ordinate references 710, 720, 730 by two angles, elevation angle θ_m (821) and azimuth angle φ_m (822).

[0068]

The following methods were traditionally used to calculate the transmit (or receive) correlation matrix, $\mathbf{R}_T$ (or $\mathbf{R}_R$). Note that for the traditional evaluation of MIMO systems it was considered sufficient to characterize the scatterers only in the horizontal plane and thus in the below Method A and Method B only the azimuth angle of scatterers are considered in the computation.

[0069]

(Method A: Direct calculation considering only azimuth angle of scatterers)

The elements of the correlation matrix can be calculated using the following formula,

$$r_{i,j} = \frac{1}{Q} \sum_{m=1}^M G(\varphi_m) \exp(j2\pi d_{i,j} \sin(\varphi_m))$$

where,

$G(\varphi_m)$ is the square of the radiation pattern along the azimuth angle φ_m in the plane formed by axis 720 and 730,

$d_{i,j}$ is the normalized (by the carrier wavelength) distance between the two antennas, and

Q is a normalization constant given by $Q = \sum_{m=1}^M G(\varphi_m)$.

[0070]

(Method B: Using distribution function for azimuth angle of scatterers)

The sub-path azimuth angle φ_m is commonly modelled using probability distributions. For example, when the sub-path azimuth angles in degrees have Laplace distribution

$$P(\varphi) = \frac{1}{\sqrt{2}\sigma} \exp\left(-\frac{\sqrt{2}|\varphi - \bar{\varphi}|}{\sigma}\right)$$

where σ is the rms azimuth angle spread and $\bar{\varphi}$ is the AoA or AoD of the path.

[0071]

In this case, the elements of the correlation matrix can be calculated using the following general formula,

$$r_{i,j} = \frac{1}{Q} \int_{\phi} P(\phi) G(\phi) \exp(j2\pi d_{i,j} \sin(\phi_m)) d\phi$$

$$Q = \int_{\phi} P(\phi) G(\phi) d\phi$$

which can be evaluated using numerical integration or Bessel series expansion (NPL5).

[0072]

For example, a following table 4 is reproduced from NPL7, showing the complex correlation values and the magnitude for different antenna spacing, variance, AoD or AoA at eNB (3-sector antenna pattern) and UE (omni-directional antenna pattern) where Laplacian distribution has been assumed for the azimuth angle of scatterers.

[table 4]

	$d_{i,j}$	σ (degrees)	$\bar{\varphi}$ (degrees)	$ r_{i,j} $	$r_{i,j}$
eNB	0.5λ	5	20	0.9688	$0.4743+0.8448i$
	0.5λ	2	50	0.9975	$-0.7367+0.6725i$
	4λ	5	20	0.3224	$-0.2144+0.2408i$
	4λ	2	50	0.8624	$0.8025+0.3158i$
	10λ	5	20	0.0704	$-0.0617+i0.034$
	10λ	2	50	0.5018	$-0.2762-i0.4190$
UE	$\lambda/2$	104	0	0.3042	-0.3042
	$\lambda/2$	35	-67.5	0.7744	$-0.6948-i0.342$
	$\lambda/2$	35	22.5	0.4399	$0.0861+0.431i$
	$\lambda/2$	35	67.5	0.7744	$-0.6948+i0.342$

[0073]

(Method C: Pragmatic approach based on capacity)

To simplify the testing of mobile equipment, a pragmatic approach not based on antenna configurations, but rather based on “artificial” values is defined for the correlation matrix (NPL4).

[0074]

The elements of the correlation matrix are calculated as follows

$$r_{i,j} = \alpha^{\left[\frac{i-j}{N-1}\right]^2}$$

where N is the number of transmit antennas and parameter α is selected based on the required ergodic capacity expectation of the MIMO channel.

[0075]

For example, a following table 5 captures the α values used in NPL4, together with the expected capacity for different MIMO channels. In the table 5, C_0 is the capacity when the antennas are completely uncorrelated, C_1 is the capacity when the antennas are fully correlated and C_λ is the capacity when the antenna correlation is given by the selected values of α_{eNB} , α_{UE} .

[table 5]

Correlation	α_{eNB}	α_{UE}	$\lambda = \frac{C_0 - C_\lambda}{C_0 - C_1}$ for different configurations of [Number of eNB antennas x Number of UE antennas]			
			1x2	2x2	4x2	4x4
Low	0	0	0	0	0	0
Medium	0.3	0.9	0.6383	0.5222	0.6664	0.8529
High	0.9	0.9	0.6383	0.7951	0.8893	0.9522

[0076]

The performance of the cellular systems can be improved considerably by techniques such as elevation beamforming and FD-MIMO. Elevation beamforming is a technique where

signal processing is used at the base station to adapt the transmit beam/(s) in both horizontal and vertical planes to improve the received signal level at a particular user while reducing the interference with other users. FD-MIMO is another technique where a large number of antennas are used at a base station to form narrow beams that can be adapted in both horizontal and
5 vertical planes.

[0077]

AAS technology such as eNB antenna implementation is being considered for a base station. In AAS technology, the RF circuitry is integrated into the antenna. This technology makes it possible to have more antennas at eNB and allows flexibility in their arrangement that is
10 controllable at a base-band level.

[0078]

Fig. 9 illustrates a scheme where 16 antennas are used at a base station such as eNB and arranged in a rectangular array.

[0079]

By arranging antennas in a rectangular array, it is now possible to perform spatial
15 processing to adapt the transmit beams in both horizontal and vertical planes. Meanwhile, the eNB antenna arranged in a linear array as shown for an example in Fig. 7 is only able to adapt the transmit beams in the horizontal plane.

[0080]

To verify the performance of these new technologies by modelling simulation, it is
20 necessary to emulate the mobile radio channels taking into account the antennas arrangement/configuration and scattering environment in both the directions.

[0081]

To emulate this MIMO channel, it is possible to follow the same general method as in
25 the case of linear antenna arrays where the antennas are arranged along one direction, i.e. tapped delay line model, 200 can be used to model each branch with tap coefficients generated for example as described with reference to the emulator system 500. The Doppler filtering approach used for linear antenna arrays can be used also for the case of rectangular antenna array.

[0082]

The method for estimation of the correlation matrix used for 520 is described below.
Advantageously, the estimation method described below also allows for simpler implementation to handle large number of antennas.

[0083]

The method estimates the correlation matrix $\mathbf{R}$ for a MIMO channel taking into account a rectangular antenna arrangement and three dimensional scattering environment. Further, a system is presented that shows how this method could be implemented with a low computational complexity and memory requirement.

5 [0084]

Fig. 9 illustrates an example of a rectangular antenna array at a base station such as LTE's eNB in a cellular system to which the current invention may be applied.

[0085]

10 The rectangular antenna array in Fig. 9 includes antennas with identical polarisation numbered from 911 to 914, from 921 to 924, from 931 to 934, from 941 to 944 arranged in a rectangular pattern in a plane 740. The plane 740 is formed by two perpendicular axes 710 and 730 (i.e. same axes, plane as in Fig. 8).

[0086]

15 For example, the rectangular antenna array at an eNB can be positioned so that a axis 720 perpendicular to the plane 740 is pointing towards the middle of a sector served by the planar array.

[0087]

20 The main aspect of the current invention is a method to generate the transmit (or receive) correlation matrix of an array of identically polarized antennas arranged rectangularly instead of a traditional array of identically polarized antennas arranged linearly in one direction, for example, horizontally. For the evaluation of the correlation matrix, this method further considers 3D scattering where, for example, the scatterers are characterized by azimuth and elevation angles instead of 2D scattering where, for example, scatterers are characterized only by azimuth angles. This is an important feature for evaluating techniques such as 3D elevation
25 beamforming and FD-MIMO.

[0088]

This transmit (or receive) correlation matrix can be used to obtain the spatial correlation matrix for implementation as the spatial correlator 520 in the exemplary system 500 to filter spatially uncorrelated tap coefficients of a tap to obtain spatially correlated tap coefficients.
30 Some examples are provided below.

[0089]

(Example A)

In the UL of a cellular system where the eNB uses a vertically polarized rectangular antenna array and UE uses a vertically polarized linear (horizontal) antenna array, the spatial

correlation matrix, $\mathbf{R}_{\text{spatial}}$ is computed as,

$$\mathbf{R}_{\text{spatial}} = \mathbf{R}_T \otimes \mathbf{R}_R$$

where $\mathbf{R}_T$ is the transmit correlation matrix for the antenna array at UE and $\mathbf{R}_R$ is the receive correlation matrix at eNB. The present method provides a means for computing $\mathbf{R}_R$.

5 [0090]

(Example B)

In the DL of a cellular system where the eNB uses a cross polarized rectangular antenna array and UE uses a vertically polarized linear (horizontal) antenna array, the spatial correlation matrix, $\mathbf{R}_{\text{spatial}}$ is computed as,

10
$$\mathbf{R}_{\text{spatial}} = \mathbf{R}_T \otimes \mathbf{\Gamma} \otimes \mathbf{R}_R$$

where $\mathbf{R}_T$ is the transmit correlation matrix for the sub-array of transmit antennas with the same polarization, $\mathbf{R}_R$ is the receive correlation matrix and $\mathbf{\Gamma}$ is the polarization correlation between the different polarizations. The method also provides a means for computing $\mathbf{R}_T$.

[0091]

15 The element $r_{i,j}$ of a transmit (or receive) correlation matrix $\mathbf{R}$ represents the correlation between the complex envelope of the signal transmitted (or received) by antenna i and the complex envelope of the signal transmitted (or received) by antenna j .

$$\mathbf{R} = \begin{bmatrix} r_{0,0} & r_{0,1} & \cdots & r_{0,15} \\ r_{1,0} & r_{1,1} & \cdots & r_{1,15} \\ \cdots & r_{i,j} & \cdots & \\ r_{15,0} & r_{15,1} & \cdots & r_{15,15} \end{bmatrix}$$

[0092]

20 In reference to the exemplary rectangular antenna array shown in Fig. 9, if the antennas 0, 1, 2 and 3 are numbered as 911, 912, 913 and 914 respectively, antennas 4, 5, 6 and 7 are numbered as 921, 922, 923 and 924 respectively, antennas 8, 9, 10 and 11 are numbered as 931, 932, 933 and 934 respectively and antennas 12, 13, 14 and 15 are numbered as 941, 942, 943 and 944 respectively, then the element $r_{0,10}$ of the correlation matrix $\mathbf{R}$ represents the correlation
25 between the complex envelope of the signal transmitted (or received) by antenna 0 (911) and antenna 10 (933).

[0093]

The elements $r_{i,j}$ of the correlation matrix can be obtained using the following

methods.

[0094]

(Method 1: Direct calculation considering azimuth and elevation angles of scatterers)

Reference will now be made to the example propagation condition in Fig. 8. A path

5 810 has many sub-paths M . The direction of a sub-path m , for example, sub-path 820 can be specified with reference to the co-ordinate reference 811, 812, 813 by two angles, elevation angle, θ_m (821) and azimuth angle, φ_m (822), and the elements of the correlation matrix can be calculated using the following general formula,

$$r_{i,j} = \frac{1}{Q} \sum_{m=1}^M G(\theta_m, \varphi_m) \exp(jk \langle \mathbf{l}(\theta_m, \varphi_m), \mathbf{d}_{i,j} \rangle)$$

10 where,

$k = 2\pi / \lambda$, and λ is the wavelength of the carrier

$G(\theta_m, \varphi_m)$ is the square of the antenna radiation pattern along the direction

(θ_m, φ_m)

$\mathbf{d}_{i,j} = \mathbf{x}_j - \mathbf{x}_i$, and $\mathbf{x}_i$ is the position vector of antenna i

15 $\mathbf{l}(\theta_m, \varphi_m)$ is the unit vector along the direction (θ_m, φ_m)

Q is a normalization constant given by $Q = \sum_{m=1}^M G(\theta_m, \varphi_m)$, and

$\langle \mathbf{x}, \mathbf{y} \rangle$ represent a dot product of two vectors $\mathbf{x}$ and $\mathbf{y}$.

[0095]

(Method 2: Using distribution function for azimuth and elevation angles of scatterers)

20 The sub-path directions (θ_m, φ_m) can be modelled using probability distributions. For example, when the sub-paths azimuth angle in degrees and elevation angle in degrees are modelled independently to have Laplace distribution, i.e.

$$P(\theta, \varphi) = P(\theta)P(\varphi)$$

$$P(\theta) = \frac{1}{\sqrt{2}\sigma_\theta} \exp\left(-\frac{\sqrt{2}|\theta - \bar{\theta}|}{\sigma_\theta}\right), \quad P(\varphi) = \frac{1}{\sqrt{2}\sigma_\varphi} \exp\left(-\frac{\sqrt{2}|\varphi - \bar{\varphi}|}{\sigma_\varphi}\right)$$

where σ_θ , σ_ϕ are the rms elevation angle spread and rms azimuth angle spread and $\bar{\theta}$, $\bar{\phi}$ are EoA/EoD and AoA/AoD of the path.

[0096]

In this case, probability distribution is used to model the sub-paths. The elements of the correlation matrix can be calculated using the following general formulas,

$$r_{i,j} = \frac{1}{Q} \int_{\theta} \int_{\phi} P(\theta, \phi) G(\theta, \phi) \exp(jk \langle \mathbf{l}(\theta, \phi), \mathbf{d}_{i,j} \rangle) d\phi d\theta$$

$$Q = \int_{\theta} \int_{\phi} P(\theta, \phi) G(\theta, \phi) d\phi d\theta$$

where,

$k = 2\pi / \lambda$, where λ is the wavelength of the carrier

10 $G(\theta, \phi)$ is the square of the antenna radiation pattern along the direction (θ, ϕ)

$\mathbf{d}_{i,j} = \mathbf{x}_j - \mathbf{x}_i$ where $\mathbf{x}_i$ is the position vector of the antenna i

$\mathbf{l}(\theta, \phi)$ is the unit vector along the direction (θ, ϕ) , and

$\langle \mathbf{x}, \mathbf{y} \rangle$ represent a dot product of two vectors $\mathbf{x}$ and $\mathbf{y}$.

[0097]

15 The above expression can be evaluated using numerical integration or spherical harmonic series expansion (NPL5).

[0098]

The above Method 1 and Method 2 can be used to generate the correlation matrix where the multiple antennas have an arbitrary location. However, when the multiple antennas are arranged in a rectangular array, then an approximate generation of the correlation matrix can be obtained with a lower computational complexity (which is significant especially when the number of antennas is high) using Method 3 below.

[0099]

(Method 3: Kronecker method (1000) comprises the following steps)

25 Step 0 (1010): This is an optional step based on what method is used in Step 1.

[0100]

If Method 3-1-1 is used in Step1, then this step consists of, grouping. Two examples are shown below.

[0101]

Example 1: $K = 1$

All the sub-paths are assumed to be in one set.

[0102]

Example 2: $K = 4$

- 5 Divide the solid angle formed by $\theta = [-\pi/2, \pi/2]$ $\phi = [-\pi, \pi]$ into K solid angles as follows:

set 1: $\theta = [-\pi/2, \bar{\theta}]$ $\phi = [-\pi, \bar{\phi}]$

set 2: $\theta = [-\pi/2, \bar{\theta}]$ $\phi = [\bar{\phi}, \pi]$

set 3: $\theta = [\bar{\theta}, \pi/2]$ $\phi = [-\pi, \bar{\phi}]$

10 set 4: $\theta = [\bar{\theta}, \pi/2]$ $\phi = [\bar{\phi}, \pi]$

[0103]

If the angle of a sub-path falls within the solid angle of the set, then that sub-path is considered to be in that set.

[0104]

15 Example 3: $K = 16$

Divide the solid angle formed by $\theta = [-\pi/2, \pi/2]$ $\phi = [-\pi, \pi]$ into K solid angles as follows. In this example $\theta_1 = \sqrt{\frac{\sigma_\theta}{2}}$ and $\phi_1 = \sqrt{\frac{\sigma_\phi}{2}}$.

[table 6]

	$\theta = [-\pi/2, \bar{\theta} - \theta_1]$	$\theta = [\bar{\theta} - \theta_1, \bar{\theta}]$	$\theta = [\bar{\theta}, \bar{\theta} + \theta_1]$	$\theta = [\bar{\theta} + \theta_1, \pi/2]$
$\phi = [-\pi, \bar{\phi} - \phi_1]$	set 1	set 2	set 3	set 4
$\phi = [\bar{\phi} - \phi_1, \bar{\phi}]$	set 5	set 6	set 7	set 8
$\phi = [\bar{\phi}, \bar{\phi} + \phi_1]$	set 9	set 10	set 11	set 12
$\phi = [\bar{\phi} + \phi_1, \pi]$	set 13	set 14	set 15	set 16

[0105]

If the angle of a sub-path falls within the solid angle of the set, then that sub-path is considered to be in that set.

[0106]

If Method 3-1-2 is used in Step 1, then this step includes the steps of, dividing the total solid angle of integration into K non-overlapping solid angles. This can be done in a manner to that in Example 2 above. If $K = 1$, then the integration is performed over the total solid angle.

[0107]

If Method 3-1-3 is used in Step 1 then this step is omitted and $K = 1$ is assumed.

[0108]

Step 1 (1020): For each set, calculate the correlation matrix $\mathbf{R}'_k$ for the row of the antenna array that forms one dimension of the rectangular array. In reference to the exemplary rectangular array system shown in Fig. 9, the linear array 950 along one direction of the rectangular array is formed by the antennas 911, 912, 913 and 914. If the antennas 0 (911), 1 (912), 2 (913) and 3 (914) are indexed as 0, 1, 2 and 3 respectively, then $\mathbf{R}'_k$ describes the following correlation matrix:

$$\mathbf{R}'_k = \begin{bmatrix} r'_{0,0} & r'_{0,1} & \cdots & r'_{0,3} \\ r'_{1,0} & r'_{1,1} & \cdots & r'_{1,3} \\ \cdots & \cdots & \cdots & \cdots \\ r'_{3,0} & r'_{3,1} & \cdots & r'_{3,3} \end{bmatrix}$$

The following methods can be used for this calculation.

[0109]

Method 3-1-1: Similar to Method 1 (i.e. “Direct calculation considering azimuth and elevation angle of scatterers”). But only the sub-paths within the corresponding set (as obtained in Step0) are used in the calculation, i.e. using notation similar to that in Method1,

$$r'_{i,j} = \frac{1}{Q_k} \sum_{m=1}^{M_k} G(\theta_m, \varphi_m) \exp(j2\pi d'_{i,j} \cos \theta_m \sin \phi_m)$$

$$Q_k = \sum_{m=1}^{M_k} G(\theta_m, \varphi_m)$$

where,

$d'_{i,j}$ is the normalized distance between the two antennas along the considered dimension of the rectangular array (normalization is with respect to λ , the wavelength of the carrier), and

M_k is the number of rays in set k .

[0110]

Method 3-1-2: Similar to Method 2 (i.e. “Using distribution function for azimuth and elevation angle of scatterers”). But the integration is performed over the solid angles of the set
5 (as obtained in Step 0), i.e. using notation similar to that in Method 2,

$$r'_{i,j} = \frac{1}{Q_k} \iint_{\theta_k \phi_k} P(\theta, \phi) G(\theta, \phi) \exp(j2\pi d'_{i,j} \cos \theta \sin \phi) d\phi d\theta$$

$$Q_k = \iint_{\theta_k \phi_k} P(\theta, \phi) G(\theta, \phi) d\phi d\theta$$

where,

$d'_{i,j}$ is the normalized distance between the two antennas along the considered dimension
10 of the rectangular array (normalization is with respect to λ , the wavelength of the carrier), and domain of integration θ_k, ϕ_k corresponds to set k .

[0111]

Method 3-1-3: A pragmatic approach, i.e. the elements of the correlation matrix are calculated as follows

$$r'_{i,j} = \alpha' \left[\frac{i-j}{N'-1} \right]^2$$

where N' is the number of transmit antennas along the considered direction and
parameter α' is defined based on the required Ergodic capacity expectation.

[0112]

Step 2 (1030): For each set, calculate the correlation matrix $\mathbf{R}_k''$ for the column of the
20 antenna array that forms the other side (refer to Step 1 above) of the rectangular array. In reference to the exemplary rectangular array system shown in Fig. 9, the linear array 960 along the other direction is formed by the antennas 911, 921, 931 and 941. If the antennas 0 (911), 4 (921), 8 (931) and 12 (941) are indexed 0, 1, 2 and 3 respectively, then $\mathbf{R}_k''$ describes the following correlation matrix:

$$\mathbf{R}_k'' = \begin{bmatrix} r''_{0,0} & r''_{0,1} & \cdots & r''_{0,3} \\ r''_{1,0} & r''_{1,1} & \cdots & r''_{1,3} \\ \cdots & \cdots & \cdots & \cdots \\ r''_{3,0} & r''_{3,1} & \cdots & r''_{3,3} \end{bmatrix}$$

[0113]

Depending on which method Method 3-1-1, Method 3-1-2, or Method 3-1-3 is used in Step 1, Method 3-2-1, Method 3-2-2 or Method 3-2-3 is respectively used in Step 2. Method 3-2-1, Method 3-2-2 and Method 3-2-3 are similar to Method 3-1-1, Method 3-1-2 and Method 3-1-3 respectively.

[0114]

Method 3-2-1: Similar to Method 1 (i.e. “Direct calculation considering azimuth and elevation angle of scatterers”). But only the sub-paths within the corresponding set (as obtained in Step 0) are used in the calculation, i.e. using notation to that in Method 1,

$$r_{i,j}'' = \frac{1}{Q_k} \sum_{m=1}^{M_k} G(\theta_m, \varphi_m) \exp(j2\pi d_{i,j}'' \sin \theta_m)$$

$$Q_k = \sum_{m=1}^{M_k} G(\theta_m, \varphi_m)$$

where,

$d_{i,j}''$ is the normalized distance between the two antennas along the considered dimension of the rectangular array (normalization is with respect to λ , the wavelength of the carrier), and M_k is the number of rays in set k and contains the same set of rays as that in Step 1.

[0115]

Method 3-2-2: Similar to Method 2 (i.e. “Using distribution function for azimuth and elevation angle of scatterers”). But the integration is performed over the solid angles of the set (as obtained in Step 0), i.e. using notation to that in Method 2,

$$r_{i,j}'' = \frac{1}{Q_k} \iint_{\theta_k \phi_k} P(\theta, \varphi) G(\theta, \varphi) \exp(j2\pi d_{i,j}'' \sin \theta) d\phi d\theta$$

$$Q_k = \iint_{\theta_k \phi_k} P(\theta, \varphi) G(\theta, \varphi) d\phi d\theta$$

where,

$d_{i,j}''$ is the normalized distance between the two antennas along the considered dimension of the rectangular array (normalization is with respect to λ , the wavelength of the carrier), and domain of integration θ_k, ϕ_k corresponds to set k .

[0116]

Method 3-2-3: A pragmatic approach, i.e. the elements of the correlation matrix are calculated as follows

$$r_{i,j}'' = \alpha''^{\left[\frac{i-j}{N''-1}\right]^2}$$

where N'' is the number of transmit antennas along the considered direction and parameter α'' is defined based on the required Ergodic capacity expectation.

[0117]

- 5 Step3 (1040): For each set, obtain the following per set correlation matrix of the rectangular array as the Kronecker product of the two correlation matrices calculated in Step 1 and Step 2:

$$\mathbf{R}_k = \mathbf{R}'_k \otimes \mathbf{R}''_k$$

[0118]

- 10 In reference to the exemplary rectangular array system shown in Fig. 9, the above Kronecker product can be explained as follows. The correlation, $r_{k_{0,10}}$ between the antenna 911 and the antenna 933 for set k is given as the product of the correlation, $r'_{k_{0,2}}$ between the antenna 911 and the antenna 913 and the correlation, $r''_{k_{0,2}}$ between the antenna 911 and the antenna 931, i.e. $r_{k_{0,10}} = r'_{k_{0,2}} r''_{k_{0,2}}$.

- 15 [0119]

Step 4 (1050): The final correlation matrix is given as a weighted sum of the per set correlation matrices.

$$\mathbf{R} = \sum_{k=1}^K \bar{Q}_k \mathbf{R}_k, \quad \bar{Q}_k = \frac{Q_k}{\sum_{k=1}^K Q_k}$$

[0120]

(Evaluations and suggestion for values)

- If Method 3-1-2 is used in Step 1, the following table 7 captures the maximum (over different AoAs and EoAs) absolute error in the estimation of the correlation values of using Method3 as compared to the exact calculation using Method 2 between 2 antennas along the diagonal of the rectangular array (i.e. $d'_{i,j} = d''_{i,j}$). 3-sector antenna pattern at eNB and Laplacian distribution for the azimuth and elevation of scatterers were assumed. From the results, the following observations were made:
- 25

The accuracy improves as K increases.

In general, the accuracy improves for lower inter antenna distances.

In general, the accuracy improves for lower rms angular spreads.

$K=1$ give reasonable accuracy when the angle of spread is low (2 degrees) and the rectangular array span is less than 4λ on either direction.

5 [table 7]

$d'_{i,j} = d''_{i,j}$	$\sigma_\theta = \sigma_\phi$ (degrees)	$\max(\text{error})$		
		K=1 (Example1)	K=4 (Example2)	K=16 (Example3)
0.5λ	5	0.03843966	0.02132586	0.02733
0.5λ	2	0.00582992	0.00296952	0.001786
4λ	5	0.70551504	0.48318426	0.247163
4λ	2	0.28650671	0.15594467	0.082246
10λ	5	0.62618114	0.54963334	0.267813
10λ	2	0.73539736	0.49681765	0.264411

[0121]

If Method 3-1-3 is used in Step 1, the following table 8 captures the capacity for different values of α', α'' in Step 1 and Step 2. From the results, it is proposed that the same values for α' and α'' can be used to test the system at different correlation levels and α', α'' can be assigned the same value of α as defined in NPL4 for low, medium and high correlations.

[table 8]

Correlation	α' (Step1)	α'' (Step2)	α_{UE}	$\lambda = \frac{C_0 - C_\lambda}{C_0 - C_1}$ for different configurations of [(Number of eNB antennas direction 1, N' x Number of eNB antennas direction 2, N'') x Number of UE antennas]
-------------	----------------------	-----------------------	---------------	--

				(2x2)x2	(4x2)x2	(4x4)x2	(4x4)x4
Low	0	0	0	0	0	0	0
Medium	0.3	0.3	0.9	0.4849	0.5493	0.5834	0.8405
High	0.9	0.9	0.9	0.7650	0.8122	0.8501	0.9424

[0122]

(System (1100) for implementation of Method 3)

The calculation of the correlation matrix as per Method 3 advantageously allows more efficient implementation of the spatial correlator. An example of the spatial correlator's system 1100 is shown in Fig. 11 for the case of 4 transmit antennas with the same polarization arranged in a 2x2 rectangular fashion and 2 receive antennas with the same polarization arranged linearly. Also K=1 in Step 0 of Method 3 is shown in the example.

[0123]

The system 1100 has three separate spatial correlators 1110, 1120 and 1130 which are used to successively correlate the input coefficients.

[0124]

If the uncorrelated input coefficients between the receive antenna i , and a transmit antenna given by index i along direction 1 and index l along direction 2 are denoted by $H_{i,j,l}$, then the operations of 1110, 1120 and 1130 are shown below.

[0125]

The notation $A_{:,j,l}$ refers to the vector $[A_{0,j,l}, A_{1,j,l}, \dots, A_{I-1,j,l}]^T$ where index i has the following range $0, 1, \dots, I-1$.

[0126]

Receive Spatial Correlator (1110) performs the following operation:

$$\bar{H}_{:,j,l} = C_R H_{:,j,l} \quad \forall j, l$$

[0127]

Transmit Spatial Correlator 1 (1120) performs the following operation:

$$\tilde{H}_{i,:,l} = C_0' \bar{H}_{i,:,l} \quad \forall i, l$$

[0128]

Transmit Spatial Correlator 2 (1130) performs the following operation:

$$\hat{H}_{i,j} = \mathbf{C}_0'' \tilde{H}_{i,j} \quad \forall i, j$$

[0129]

The implementation shown in this example can be similarly extended to other values of K in Step 0 and can be similarly extended to handle cross polarized antenna arrays. This implementation allows the order of the correlators 1110, 1120, 1130 to be interchanged and thus is computationally efficient and requires lower memory resources.

[0130]

Accordingly, the method can be used to obtain spatially correlated coefficients when the correlation matrix is obtained as described above. The uncorrelated input coefficients between the receive antenna i , and transmit antenna given by index j along direction 1 and index l along direction 2 are denoted by $H_{i,j,l}$.

[0131]

The method includes obtaining the matrix square root of a receive correlation matrix, a transmit correlation matrix along direction 1, and a transmit correlation matrix along direction 2 using Cholesky decomposition:

$$\begin{aligned} \mathbf{R}_R &= \mathbf{C}_R \mathbf{C}_R^H \\ \mathbf{R}' &= \mathbf{C}' \mathbf{C}'^H \\ \mathbf{R}'' &= \mathbf{C}'' \mathbf{C}''^H \end{aligned}$$

[0132]

Introducing receiver correlation for each transmit antenna:

$$\bar{H}_{:,j,l} = \mathbf{C}_R H_{:,j,l} \quad \forall j, l$$

[0133]

Introducing transmit correlation along direction 1 for each transmit antenna along direction 2 and receive antenna:

$$\tilde{H}_{i,:,l} = \mathbf{C}'_0 \bar{H}_{i,:,l} \quad \forall i, l$$

[0134]

Introducing transmit correlation along direction 2 for each transmit antenna along direction 1 and receive antenna:

$$\hat{H}_{i,j,:} = \mathbf{C}_0'' \tilde{H}_{i,j,:} \quad \forall i, j$$

[0135]

The order of introducing the correlation above can be arbitrary.

[0136]

Pragmatic spatial correlation matrices can also be determined based on Method 3. The pragmatic spatial correlation matrices are used for the designing, evaluating and testing of 3D beamforming, FD-MIMO algorithms where a rectangular antenna array is used at eNB and a linear array is used at UE:

$$\mathbf{R}_{\text{spatial}} = \mathbf{R}'_{\text{eNB}} \otimes \mathbf{R}''_{\text{eNB}} \otimes \mathbf{R}_{\text{UE}}$$

where $r'_{i,j} = \alpha' \left[\frac{i-j}{N'-1} \right]^2$ are the elements of matrix $\mathbf{R}'_{\text{eNB}}$, $r''_{i,j} = \alpha'' \left[\frac{i-j}{N''-1} \right]^2$ are the elements of matrix $\mathbf{R}''_{\text{eNB}}$ and $r_{i,j} = \beta \left[\frac{i-j}{N-1} \right]^2$ are the elements of matrix $\mathbf{R}_{\text{UE}}$. N' , N'' are the number of eNB antennas along the two adjacent sides of the rectangular antenna array and N is the number of antennas at the UE.

[0137]

The values for α' , α'' and β for different correlation levels are proposed in the following table 9:

[table 9]

Correlation	α'	α''	β
Low	0	0	0
Medium	0.3	0.3	0.9
High	0.9	0.9	0.9

[0138]

Advantageously, the set of correlation matrices determined above can be used in realizing a computerised simulation system for designing, evaluating and validating features/functions related to 3D-beam forming and/or full dimensional MIMO.

[0139]

In addition, the correlation matrices can also be used in implementing apparatus such as test equipment utilized in a laboratory for validating an advanced base station and user equipment supporting 3D beamforming and full dimension MIMO techniques.

[0140]

Advantageously, the method can be used for generating a transmit (or receive) correlation matrix for a rectangular antenna array that can be used for link level emulation of a

MIMO wireless channel that is accurate enough for evaluating and testing wireless systems that employ 3D elevation beamforming and FD-MIMO technologies and yet computationally efficient for a large number of antennas.

[0141]

5 Moreover, a computationally efficient and memory efficient system is advantageously provided for implementing the spatial correlation based on the method.

[0142]

10 In the present specification and claims (if any), the word 'comprising' and its derivatives including 'comprises' and 'comprise' include each of the stated integers but does not exclude the inclusion of one or more further integers.

[0143]

15 Reference throughout this specification to 'one embodiment' or 'an embodiment' means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, the phrases 'in one embodiment' or 'in an embodiment' in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the particular features, structures, or characteristics of the various embodiments may be combined in any suitable manner in one or more combinations.

[0144]

20 In compliance with the statute which one, the invention has been described in language more or less specific to structural or methodical features. It is to be understood that the invention is not limited to specific features shown or described since the means herein described comprises preferred forms of putting the invention into effect. The invention is, therefore, claimed in any of its forms or modifications within the proper scope of the appended claims (if
25 any) appropriately interpreted by those skilled in the art.

[0145]

Various other modifications will be apparent to those skilled in the art and thus will not be described in further detail here.

[0146]

30 This software can be stored in various types of non-transitory computer readable media and thereby supplied to computers. The non-transitory computer readable media includes various types of tangible storage media. Examples of the non-transitory computer readable media include a magnetic recording medium (such as a flexible disk, a magnetic tape, and a hard disk drive), a magneto-optic recording medium (such as a magneto-optic disk), a CD-ROM

(Read Only Memory), a CD-R, and a CD-R/W, and a semiconductor memory (such as a mask ROM, a PROM (Programmable ROM), an EPROM (Erasable PROM), a flash ROM, and a RAM (Random Access Memory)). Further, the program can be supplied to computers by using various types of transitory computer readable media. Examples of the transitory computer readable media include an electrical signal, an optical signal, and an electromagnetic wave. The transitory computer readable media can be used to supply programs to computer through a wire communication path such as an electrical wire and an optical fiber, or wireless communication path.

[0147]

This application is based upon and claims the benefit of priority from Australian Provisional Patent Application No.2013902848 filed on 31 July, 2013, the disclosure of which is incorporated herein in its entirety by reference.

Reference Signs List

15	[0148]
100	wireless transmission paths
110	scattering object
111	scattering object
121	transmitter
20 131	receiver
141	path
142	path
151	sub-path
152	sub-path
25 153	sub-path
154	sub-path
155	sub-path
156	sub-path
200	tapped delay line system
30 210	delay
221	tap coefficient
222	tap coefficient
223	tap coefficient
224	tap coefficient

	230	SUM
	300	tap
	311	complex white Gaussian noise generator
	321	Doppler filter
5	400	antenna configuration
	462	transmitter
	463	transmitter
	464	transmitter
	465	transmitter
10	472	receiver
	473	receiver
	481	channel
	500	system
	510	sub-system
15	520	spatial correlator
	521	Kronecker product
	522	Cholesky decomposition
	600	antenna array
	662	antenna
20	663	antenna
	664	antenna
	665	antenna
	672	antenna
	673	antenna
25	700	linear antenna array
	710	axis
	720	axis
	730	axis
	740	plane
30	751	transmit antenna
	752	transmit antenna
	753	transmit antenna
	754	transmit antenna
	800	group of transmission paths

	810	path
	811	co-ordinate reference
	812	co-ordinate reference
	820	sub-path
5	821	elevation angle
	822	azimuth angle
	900	rectangular antenna array
	911	antenna
	912	antenna
10	913	antenna
	914	antenna
	921	antenna
	931	antenna
	933	antenna
15	941	antenna
	950	linear array
	960	linear array
	970	horizontal array antennae
	980	horizontal array antennae
20	990	vertical array antennae
	1100	system
	1110	receive spatial correlator
	1120	transmit spatial correlator
	1130	transmit spatial correlator

CLAIMS

[Claim 1]

A computer implemented simulator operable to determine a first correlation matrix (R) simulating transmission path correlation between a base station and user equipment antennas, the first correlation matrix (R) being determined for simulated wireless transmission paths of a plurality of antennas having the same polarization and arranged in a two-dimensional array, the computer implemented simulator being configured to:

determine one or more second correlation matrices (R_k') for a subset of the antennas which form a first side of the array,

determine one or more third correlation matrices (R_k'') for a subset of the antennas which form a second side of the array,

determine one or more fourth correlation matrices (R_k), each fourth correlation matrix being determined based on a Kronecker product ($R_k = R_k' \otimes R_k''$) of each second correlation matrix (R_k') and a corresponding third correlation matrix (R_k''), and

determine the first correlation matrix (R) simulating transmission path correlation by determining a weighted sum of the one or more fourth correlation matrices (R_k).

[Claim 2]

A computer implemented simulator as claimed in claim 1, wherein the array is rectangular and the second side is adjacent the first side, the computer implemented simulator being configured to:

determine a number of sets (K) for grouping the simulated wireless transmission paths,

determine weight factors associated with the number of sets (K), and

determine the weighted sum of the one or more fourth correlation matrices (R_k) using the weight factors.

[Claim 3]

A computer implemented simulator as claimed in claim 2, wherein the computer implemented simulator is configured to:

divide a three-dimensional transmission space of the transmission paths into a number of sectors equal to the number of sets (K), each sector being defined by an elevation angle range (θ) and an azimuth angle range (ϕ), and

group the transmission paths which have an elevation angle (θ) and an azimuth angle (φ) falling within the same sector so as to form K sets of transmission paths.

[Claim 4]

5 A computer implemented simulator as claimed in claim 3, wherein the computer implemented simulator is configured to determine the one or more second correlation matrices

(R_k) by determining a second correlation matrix $R'_k = \begin{bmatrix} r'_{0,0} & r'_{0,1} & \dots & r'_{0,j} \\ r'_{1,0} & r'_{1,1} & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r'_{i,0} & \dots & \dots & r'_{i,j} \end{bmatrix}$ for each set (k) of

transmission paths using the following equation:

$$r'_{i,j} = \frac{1}{Q_k} \sum_{m=1}^{M_k} G(\theta_m, \varphi_m) \exp(j2\pi d'_{i,j} \cos \theta_m \sin \phi_m)$$

$$Q_k = \sum_{m=1}^{M_k} G(\theta_m, \varphi_m)$$

10 wherein $d'_{i,j}$ is a normalized distance with respect to a wavelength (λ) of a carrier between two antennas (i, j) along the first side of the two-dimensional array, θ_m is an angle that sub-path (m) extends to a reference plane formed by the first side of the two-dimensional array and a direction perpendicular to the array, φ_m is an angle between the projection of the sub-path (m) on the reference plane and a direction perpendicular to the rectangular array, and M_k is the

15 number of transmission paths in a set (k).

[Claim 5]

A computer implemented simulator as claimed in claim 3, wherein the computer implemented simulator is configured to determine one or more second correlation matrices (R_k)

20 by determining a second correlation matrix $R'_k = \begin{bmatrix} r'_{0,0} & r'_{0,1} & \dots & r'_{0,j} \\ r'_{1,0} & r'_{1,1} & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r'_{i,0} & \dots & \dots & r'_{i,j} \end{bmatrix}$ for each set (k) of

transmission paths using the following equation:

$$r'_{i,j} = \frac{1}{Q_k} \int \int_{\theta_k \phi_k} P(\theta, \varphi) G(\theta, \varphi) \exp(j2\pi d'_{i,j} \cos \theta \sin \phi) d\phi d\theta$$

$$Q_k = \int \int_{\theta_k \phi_k} P(\theta, \varphi) G(\theta, \varphi) d\phi d\theta$$

wherein $d'_{i,j}$ is a normalized distance with respect to a wavelength (λ) of a carrier between two antennas (i, j) along the first side of the two-dimensional array, θ is an elevation angle above a reference plane formed by the first side of the two-dimensional array and a direction perpendicular to the array, φ is an angle measured from a direction perpendicular to the array on the reference plane, and a domain of integration θ_k, ϕ_k corresponds to set k .

[Claim 6]

A computer implemented simulator as claimed in claim 1, wherein the computer implemented simulator is configured to determine the second correlation matrix

$$\mathbf{R}'_k = \begin{bmatrix} r'_{0,0} & r'_{0,1} & \dots & r'_{0,j} \\ r'_{1,0} & r'_{1,1} & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r'_{i,0} & \dots & \dots & r'_{i,j} \end{bmatrix} \text{ using the following equation:}$$

$$r'_{i,j} = \alpha' \left[\frac{i-j}{N'-1} \right]^2$$

wherein N' is the number of antennas along the first side of the array, and parameter α' is defined based on a required Ergodic capacity expectation.

[Claim 7]

A computer implemented simulator as claimed in claim 3, wherein the computer implemented simulator is configured to determine one or more third correlation matrices ($\mathbf{R}_k''$)

$$\text{by determining a third correlation matrix } \mathbf{R}_k'' = \begin{bmatrix} r''_{0,0} & r''_{0,1} & \dots & r''_{0,j} \\ r''_{1,0} & r''_{1,1} & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r''_{i,0} & \dots & \dots & r''_{i,j} \end{bmatrix} \text{ for each set } (k) \text{ of}$$

transmission paths using the following equation:

$$r''_{i,j} = \frac{1}{Q_k} \sum_{m=1}^{M_k} G(\theta_m, \varphi_m) \exp(j2\pi d''_{i,j} \sin \theta_m)$$

$$Q_k = \sum_{m=1}^{M_k} G(\theta_m, \varphi_m)$$

wherein $d''_{i,j}$ is a normalized distance with respect to a wavelength (λ) of a carrier

between two antennas (i, j) along the second side of the two-dimensional array, θ_m is an angle that sub-path (m) extends to a reference plane formed by the first side of the two-dimensional array and a direction perpendicular to the array, ϕ_m is an angle between the projection of the sub-path on the reference plane and the direction perpendicular to the array, and M_k is the number of transmission paths in a set (k).

[Claim 8]

A computer implemented simulator as claimed in claim 3, wherein the computer implemented simulator is configured to determine one or more third correlation matrices (R_k)

10 by determining a third correlation matrix $R_k = \begin{bmatrix} r_{0,0}'' & r_{0,1}'' & \dots & r_{0,j}'' \\ r_{1,0}'' & r_{1,1}'' & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r_{i,0}'' & \dots & \dots & r_{i,j}'' \end{bmatrix}$ for each set (k) of

transmission paths using the following equation:

$$r_{i,j}'' = \frac{1}{Q_k} \int \int_{\theta_k, \phi_k} P(\theta, \phi) G(\theta, \phi) \exp(j2\pi d_{i,j}'' \sin \theta) d\phi d\theta$$

$$Q_k = \int \int_{\theta_k, \phi_k} P(\theta, \phi) G(\theta, \phi) d\phi d\theta$$

15 wherein $d_{i,j}''$ is the normalized distance with respect to a wavelength (λ) of a carrier between two antennas (i, j) along the second side of the two-dimensional array, θ is an elevation angle above a reference plane formed by the first side of the two dimensional array and a direction perpendicular to the array, ϕ is the angle measured from a direction perpendicular to the array on the reference plane, and a domain of integration θ_k, ϕ_k corresponds to set k .

20 [Claim 9]

A computer implemented simulator as claimed in claim 1, wherein the computer implemented simulator is configured to determine a third correlation matrix

$R_k = \begin{bmatrix} r_{0,0}'' & r_{0,1}'' & \dots & r_{0,j}'' \\ r_{1,0}'' & r_{1,1}'' & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r_{i,0}'' & \dots & \dots & r_{i,j}'' \end{bmatrix}$ using the following equation:

$$r_{i,j}'' = \alpha'' \left[\frac{i-j}{N''-1} \right]^2$$

wherein N'' is the number of antennas along the second side of the array, and parameter α'' is defined based on a required Ergodic capacity expectation.

[Claim 10]

A computer implemented simulator as claimed in claim 1, wherein the computer implemented simulator is further operable to determine spatially correlated coefficients for the simulated wireless transmission paths by being configured to:

obtain a matrix square root of a receive correlation matrix,

$$\mathbf{R}_R = \mathbf{C}_R \mathbf{C}_R^H$$

obtain a matrix square root of a transmit correlation matrix along direction 1,

$$\mathbf{R}' = \mathbf{C}' \mathbf{C}'^H$$

obtain a matrix square root of a transmit correlation matrix along direction 2,

$$\mathbf{R}'' = \mathbf{C}'' \mathbf{C}''^H$$

determine a receiver correlation for each transmit antenna:

$$\bar{H}_{i,j,l} = \mathbf{C}_R H_{i,j,l} \quad \forall j, l$$

determine a transmit correlation along direction 1 for each transmit antenna along direction 2 and receive antenna:

$$\tilde{H}_{i,j,l} = \mathbf{C}'_0 \bar{H}_{i,j,l} \quad \forall i, l$$

determine a transmit correlation along direction 2 for each transmit antenna along direction 1 and receive antenna:

$$\hat{H}_{i,j,l} = \mathbf{C}''_0 \tilde{H}_{i,j,l} \quad \forall i, j$$

wherein $H_{i,j,l}$ denotes uncorrelated input coefficients between a receive antenna i , a transmit antenna given by index j along direction 1, and a transmit antenna given by index l along direction 2.

[Claim 11]

A computer implemented simulator as claimed in claim 1, wherein the computer implemented simulator is further operable to determine a spatial correlation matrix ($\mathbf{R}_{spatial}$) for facilitating the designing, evaluating and testing of three-dimensional beamforming, FD-MIMO algorithms in which a rectangular antenna array is used at a base station node and a linear antenna array is used at a user equipment, the spatial correlation matrix being determined based on the following Kronecker product formula:

$$\mathbf{R}_{spatial} = \mathbf{R}'_{eNB} \otimes \mathbf{R}''_{eNB} \otimes \mathbf{R}_{UE}$$

wherein

$\mathbf{R}'_{eNB}$ is a correlation matrix of the rectangular antenna array at the base station node,

and elements of matrix $\mathbf{R}'_{eNB}$ can be determined using formula $r'_{i,j} = \alpha' \left[\frac{i-j}{N'-1} \right]^2$,

$\mathbf{R}''_{eNB}$ is a further correlation matrix of the rectangular antenna array at the base station

5 node, and elements of matrix $\mathbf{R}''_{eNB}$ can be determined using formula $r''_{i,j} = \alpha'' \left[\frac{i-j}{N''-1} \right]^2$,

$\mathbf{R}_{UE}$ is a correlation matrix of the linear antenna array at the user equipment, and

elements of matrix $\mathbf{R}_{UE}$ can be determined using formula: $r_{i,j} = \beta \left[\frac{i-j}{N-1} \right]^2$,

N' , N'' are the numbers of antennas at the base station node along two adjacent sides of the rectangular antenna array, respectively,

10 N is the number of antennas at the user equipment, and

values for α' , α'' and β for different correlation levels are selected from the following table:

[table 1]

Correlation levels	α'	α''	β
Low	0	0	0
Medium	0.3	0.3	0.9
High	0.9	0.9	0.9

15 [Claim 12]

A method for determining a first correlation matrix ($\mathbf{R}$) simulating transmission path correlation between a base station and user equipment antennas, the first correlation matrix ($\mathbf{R}$) being determined for simulated wireless transmission paths of a plurality of antennas having the same polarization and arranged in a two-dimensional array, the method including the steps of:

20 determining one or more second correlation matrices ($\mathbf{R}_k'$) for a subset of the antennas which form a first side of the array,

determining one or more third correlation matrices ($\mathbf{R}_k''$) for a subset of the antennas which form a second side of the array adjacent the first side,

25 determining one or more fourth correlation matrices ($\mathbf{R}_k$), each fourth correlation matrix being determined based on a Kronecker product ($\mathbf{R}_k = \mathbf{R}_k' \otimes \mathbf{R}_k''$) of each second correlation matrix ($\mathbf{R}_k'$) and a corresponding third correlation matrix ($\mathbf{R}_k''$), and

determining the first correlation matrix (R) simulating transmission path correlation by determining a weighted sum of the one or more fourth correlation matrices (R_k).

[Claim 13]

5 The method as claimed in claim 12, wherein the array is rectangular and the second side is adjacent the first side, the method including:

determining a number of sets (K) for grouping the simulated wireless transmission paths,

determining weight factors associated with the number of sets (K), and

10 determining the weighted sum of the one or more fourth correlation matrices (R_k) using the weight factors.

[Claim 14]

The method as claimed in claim 13, including:

15 dividing a three-dimensional transmission space of the transmission paths into a number of sectors equal to the number of sets (K), each sector being defined by an elevation angle range (θ) and an azimuth angle range (ϕ), and

grouping the transmission paths which have an elevation angle (θ) and an azimuth angle (ϕ) falling within the same sector so as to form K sets of transmission paths.

20 [Claim 15]

The method as claimed in claim 14, including

determining the one or more second correlation matrices (R'_k) by determining a second

correlation matrix $\mathbf{R}'_k = \begin{bmatrix} r'_{0,0} & r'_{0,1} & \dots & r'_{0,j} \\ r'_{1,0} & r'_{1,1} & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r'_{i,0} & \dots & \dots & r'_{i,j} \end{bmatrix}$ for each set (k) of transmission paths using the

following equation:

$$r'_{i,j} = \frac{1}{Q_k} \sum_{m=1}^{M_k} G(\theta_m, \phi_m) \exp(j2\pi d'_{i,j} \cos \theta_m \sin \phi_m)$$

$$Q_k = \sum_{m=1}^{M_k} G(\theta_m, \phi_m)$$

25 wherein $d'_{i,j}$ is a normalized distance with respect to a wavelength (λ) of a carrier between two antennas (i, j) along the first side of the two-dimensional array, θ_m is an angle that

sub-path (m) extends to a reference plane formed by the first side of the two-dimensional array and a direction perpendicular to the two-dimensional array, φ_m is an angle between a projection of the sub-path (m) on the reference plane and a direction perpendicular to the array, and M_k is the number of transmission paths in a set (k).

5

[Claim 16]

The method as claimed in claim 14, including

determining one or more second correlation matrices (R'_k) by determining a second

correlation matrix $R'_k = \begin{bmatrix} r'_{0,0} & r'_{0,1} & \dots & r'_{0,J} \\ r'_{1,0} & r'_{1,1} & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r'_{i,0} & \dots & \dots & r'_{i,J} \end{bmatrix}$ for each set (k) of transmission paths using the

10 following equation:

$$r'_{i,j} = \frac{1}{Q_k} \int \int_{\theta_k \phi_k} P(\theta, \varphi) G(\theta, \varphi) \exp(j2\pi d'_{i,j} \cos\theta \sin\phi) d\phi d\theta$$

$$Q_k = \int \int_{\theta_k \phi_k} P(\theta, \varphi) G(\theta, \varphi) d\phi d\theta$$

wherein $d'_{i,j}$ is the normalized distance with respect to a wavelength (λ) of a carrier between two antennas (i, j) along the first side of the two-dimensional array, θ is an elevation angle above a reference plane formed by the first side of the two-dimensional array and direction perpendicular to the array, φ is an angle measured from a direction perpendicular to the array on the reference plane, and a domain of integration θ_k, ϕ_k corresponds to set k .

15

[Claim 17]

20 A method as claimed in claims 12, including determining a second correlation matrix

$R'_k = \begin{bmatrix} r'_{0,0} & r'_{0,1} & \dots & r'_{0,J} \\ r'_{1,0} & r'_{1,1} & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r'_{i,0} & \dots & \dots & r'_{i,J} \end{bmatrix}$ using the following equation:

$$r'_{i,j} = \alpha' \left[\frac{i-j}{N'-1} \right]^2$$

wherein N' is the number of antennas along the first side of the array, and parameter α' is defined based on a required Ergodic capacity expectation.

[Claim 18]

The method as claimed in claim 14, including determining one or more third correlation

matrices (R_k'') by determining a third correlation matrix $R_k'' = \begin{bmatrix} r_{0,0}'' & r_{0,1}'' & \dots & r_{0,j}'' \\ r_{1,0}'' & r_{1,1}'' & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r_{i,0}'' & \dots & \dots & r_{i,j}'' \end{bmatrix}$ for each set

5 (k) of transmission paths using the following equation:

$$r_{i,j}'' = \frac{1}{Q_k} \sum_{m=1}^{M_k} G(\theta_m, \varphi_m) \exp(j2\pi d_{i,j}'' \sin \theta_m)$$

$$Q_k = \sum_{m=1}^{M_k} G(\theta_m, \varphi_m)$$

wherein $d_{i,j}''$ is a normalized distance with respect to a wavelength (λ) of a carrier between two antennas (i, j) along the second side of the two-dimensional array, θ_m is an angle that sub-path (m) extends to a reference plane formed by the first side of the two-dimensional array and a direction perpendicular to the array, φ_m is an angle between a projection of the sub-path (m) on the reference plane and the direction perpendicular to the array, and M_k is the number of transmission paths in a set (k).

[Claim 19]

15 The method as claimed in claim 14, including determining the one or more third

correlation matrices (R_k'') by determining a third correlation matrix $R_k'' = \begin{bmatrix} r_{0,0}'' & r_{0,1}'' & \dots & r_{0,j}'' \\ r_{1,0}'' & r_{1,1}'' & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r_{i,0}'' & \dots & \dots & r_{i,j}'' \end{bmatrix}$

for each set (k) of transmission paths using the following equation:

$$r_{i,j}'' = \frac{1}{Q_k} \int \int_{\theta_k, \phi_k} P(\theta, \varphi) G(\theta, \varphi) \exp(j2\pi d_{i,j}'' \sin \theta) d\phi d\theta$$

$$Q_k = \int \int_{\theta_k, \phi_k} P(\theta, \varphi) G(\theta, \varphi) d\phi d\theta$$

20 wherein $d_{i,j}''$ is a normalized distance with respect to a wavelength (λ) of a carrier between two antennas (i, j) along the second side of the two-dimensional array, θ is an elevation angle above a reference plane formed by the first side of the two-dimensional array and

a direction perpendicular to the array, φ is an angle measured from a direction perpendicular to the array on the reference plane, and a domain of integration θ_k, ϕ_k corresponds to set k .

[Claim 20]

5 The method as claimed in claim 12, including determining a third correlation matrix

$$\mathbf{R}_k'' = \begin{bmatrix} r_{0,0}'' & r_{0,1}'' & \cdots & r_{0,j}'' \\ r_{1,0}'' & r_{1,1}'' & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ r_{i,0}'' & \cdots & \cdots & r_{i,j}'' \end{bmatrix} \text{ using the following equation:}$$

$$r_{i,j}'' = \alpha'' \left[\frac{i-j}{N''-1} \right]^2$$

wherein N'' is the number of antennas along the second side of the array, and parameter α'' is defined based on a required Ergodic capacity expectation.

10

[Claim 21]

The method as claimed in claim 12, further including determining spatially correlated coefficients for the simulated wireless transmission paths by:

obtaining a matrix square root of a receive correlation matrix,

15

$$\mathbf{R}_R = \mathbf{C}_R \mathbf{C}_R^H$$

obtain a matrix square root of a transmitting correlation matrix along direction 1,

$$\mathbf{R}' = \mathbf{C}' \mathbf{C}'^H$$

obtain a matrix square root of a transmitting correlation matrix along direction 2,

$$\mathbf{R}'' = \mathbf{C}'' \mathbf{C}''^H$$

20

determining receiver correlation for each transmit antenna using the following formula:

$$\bar{H}_{:,j,l} = \mathbf{C}_R H_{:,j,l} \quad \forall j, l$$

determining transmit correlation along direction 1 for each transmit antenna along direction 2 and receive antenna using the following formula:

$$\tilde{H}_{i,:} = \mathbf{C}_0' \bar{H}_{i,:} \quad \forall i, l$$

25

determining transmit correlation along direction 2 for each transmit antenna along direction 1 and receive antenna using the following formula:

$$\hat{H}_{i,j,:} = \mathbf{C}_0'' \tilde{H}_{i,j,:} \quad \forall i, j$$

wherein $H_{i,j,l}$ denotes uncorrelated input coefficients between a receive antenna i , a transmit antenna given by index j along direction 1, and a transmit antenna given by index l along direction 2.

[Claim 22]

- 5 The method as claimed in claim 12, further including determining a spatial correlation matrix ($\mathbf{R}_{\text{spatial}}$) for facilitating the designing, evaluating and testing of three-dimensional beamforming, FD-MIMO algorithms in which a rectangular antenna array is used at a base station node and a linear antenna array is used at a user equipment, the spatial correlation matrix being determined based on the following Kronecker product formula:

$$10 \quad \mathbf{R}_{\text{spatial}} = \mathbf{R}'_{eNB} \otimes \mathbf{R}''_{eNB} \otimes \mathbf{R}_{UE}$$

wherein

$\mathbf{R}'_{eNB}$ is a correlation matrix of the rectangular antenna array at the base station node,

and elements of matrix $\mathbf{R}'_{eNB}$ can be determined using the formula: $r'_{i,j} = \alpha' \left[\frac{i-j}{N'-1} \right]^2$,

$\mathbf{R}''_{eNB}$ is a further correlation matrix of the rectangular antenna array at the base station

- 15 node, and elements of matrix $\mathbf{R}''_{eNB}$ can be determined using the formula: $r''_{i,j} = \alpha'' \left[\frac{i-j}{N''-1} \right]^2$,

$\mathbf{R}_{UE}$ is a correlation matrix of the linear antenna array at the user equipment, and

elements of matrix $\mathbf{R}_{UE}$ can be determined using the formula: $r_{i,j} = \beta \left[\frac{i-j}{N-1} \right]^2$,

N' , N'' are the numbers of antennas at the base station node along two adjacent sides of the rectangular antenna array,

- 20 N is the number of antennas at the user equipment, and

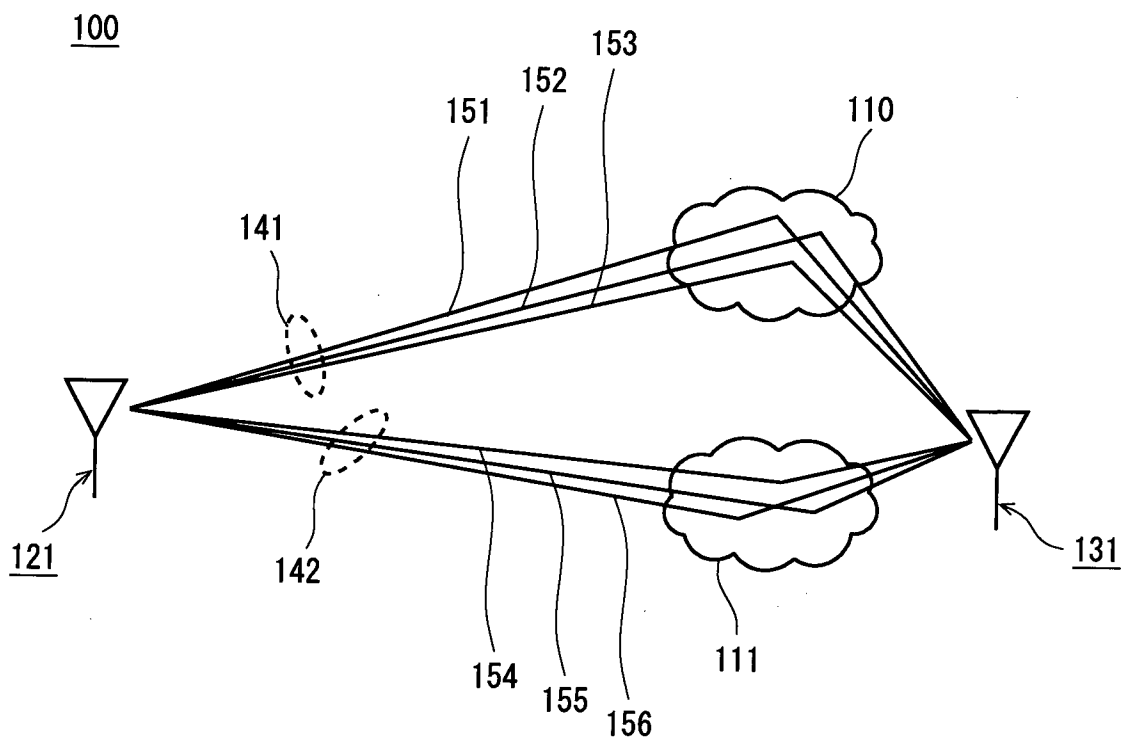
values for α' , α'' and β for different correlation levels are selected from the following table:

[table 2]

Correlation levels	α'	α''	β
Low	0	0	0
Medium	0.3	0.3	0.9
High	0.9	0.9	0.9

1/11

Fig. 1



2/11

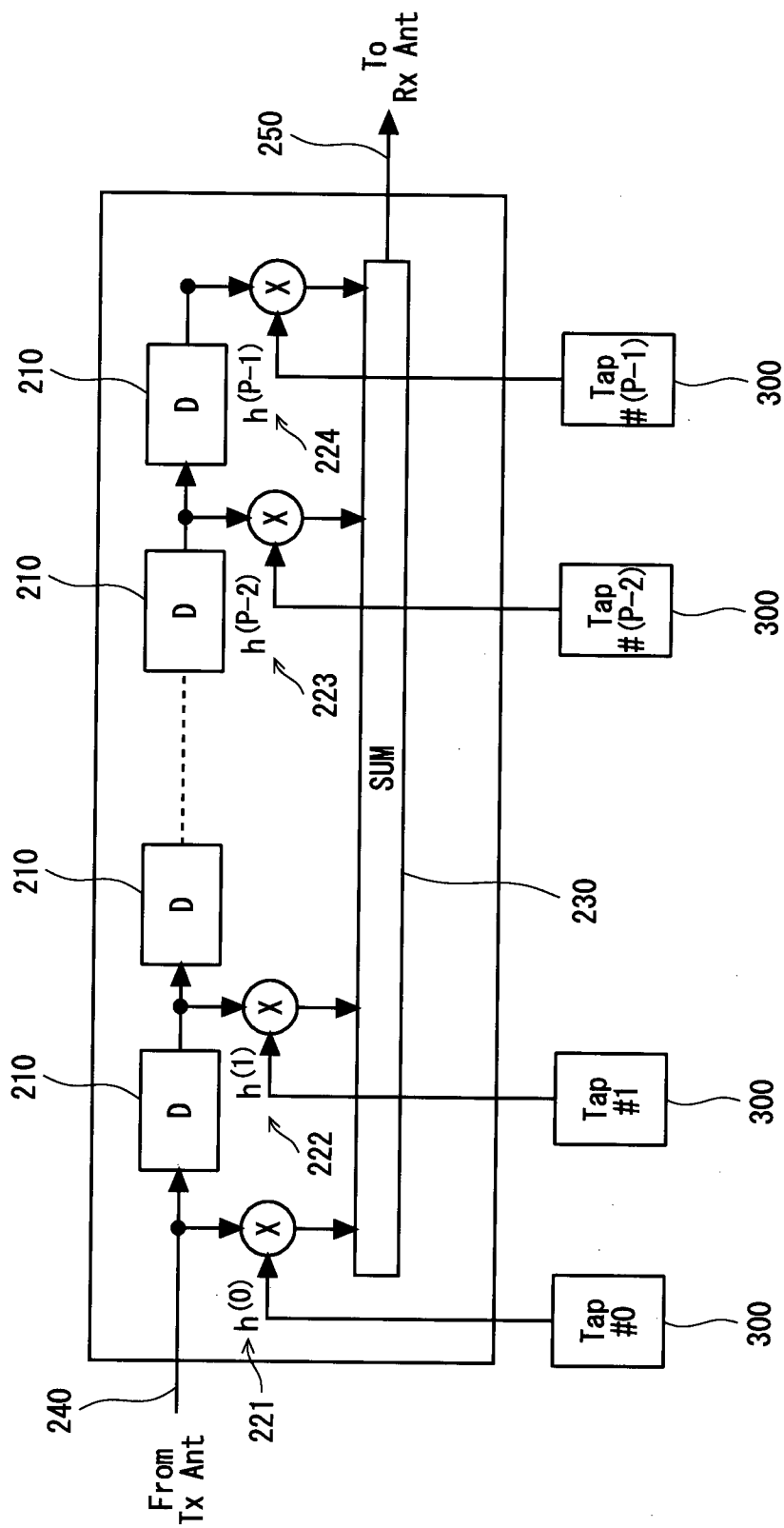
200

Fig. 2

3/11

Fig. 3

300

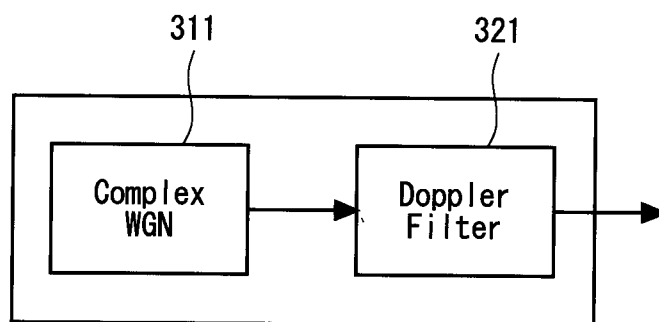
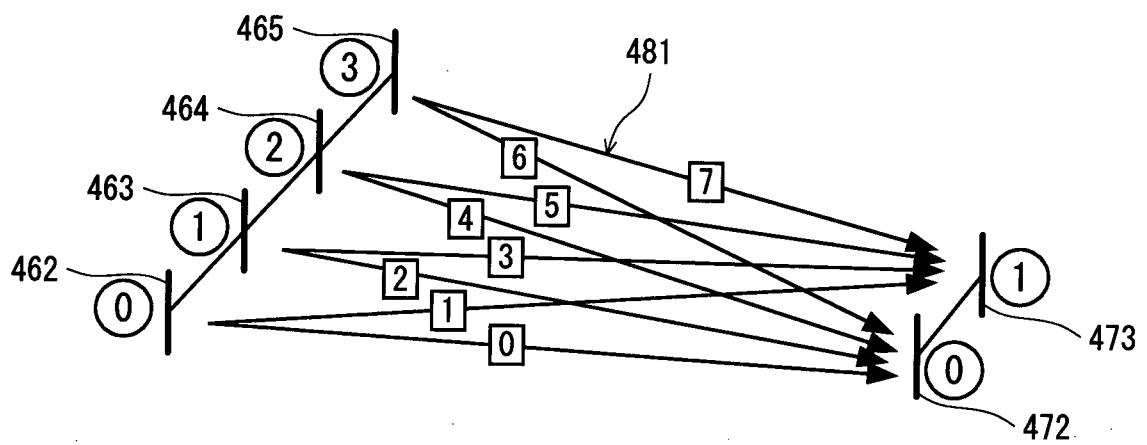


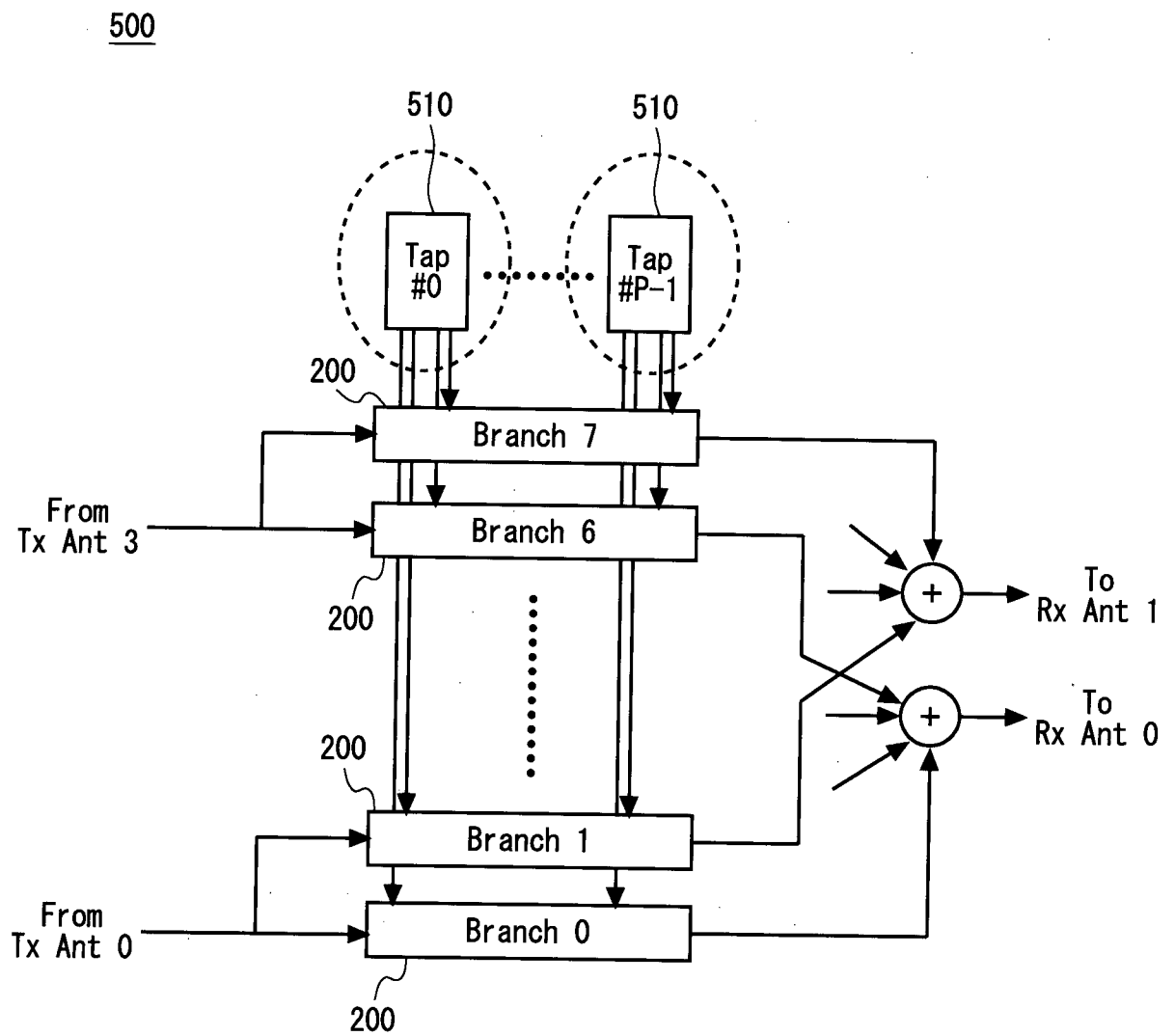
Fig. 4

400



4/11

Fig. 5A



5/11

Fig. 5B

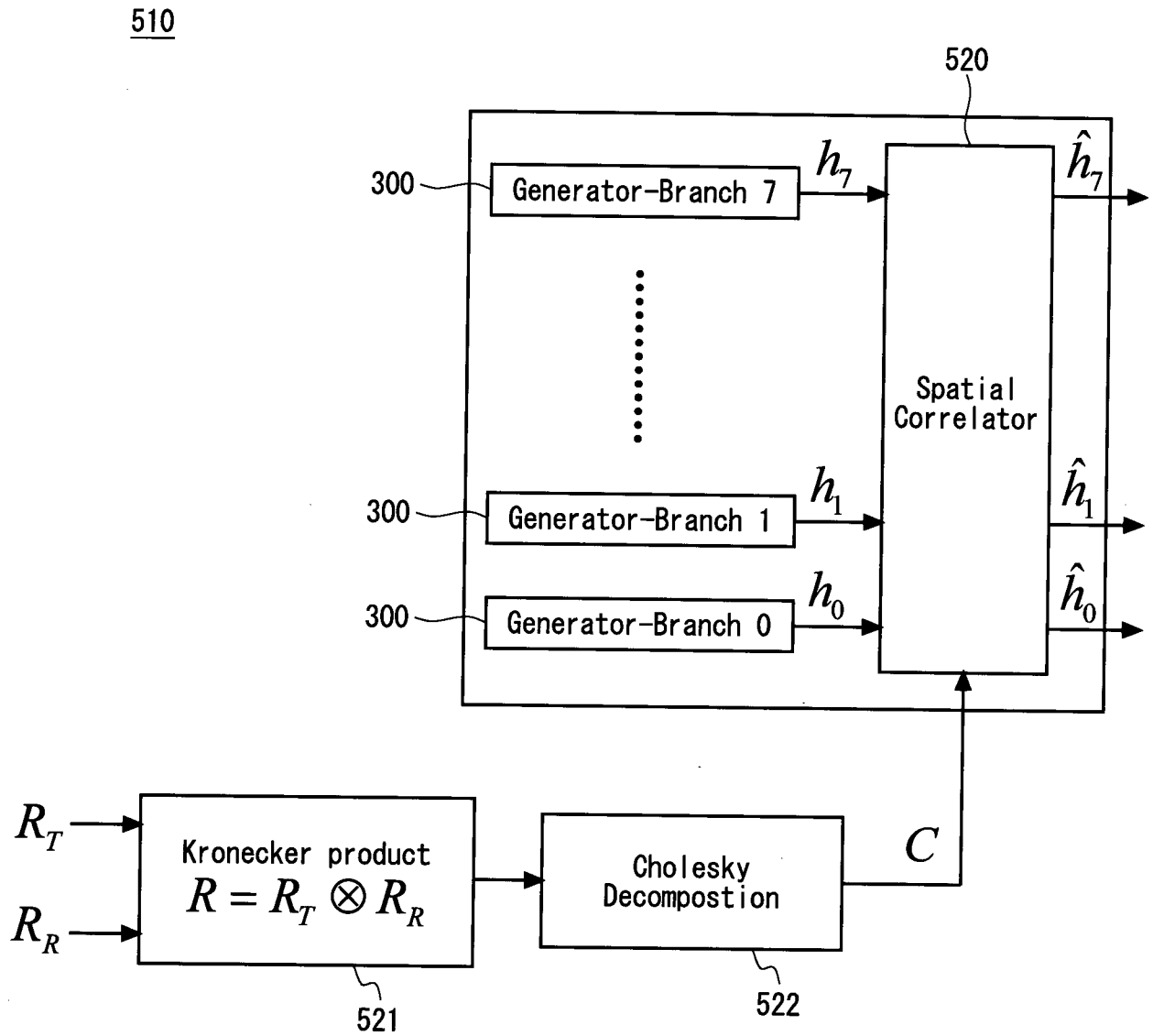


Fig. 6

600

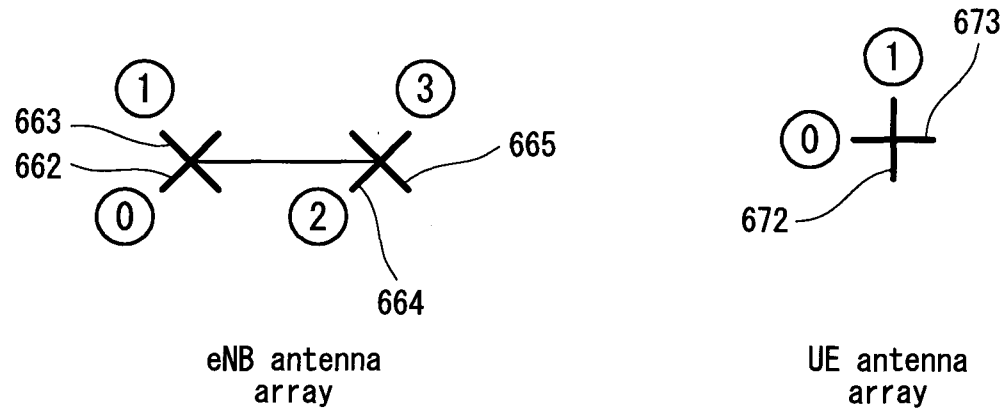


Fig. 7

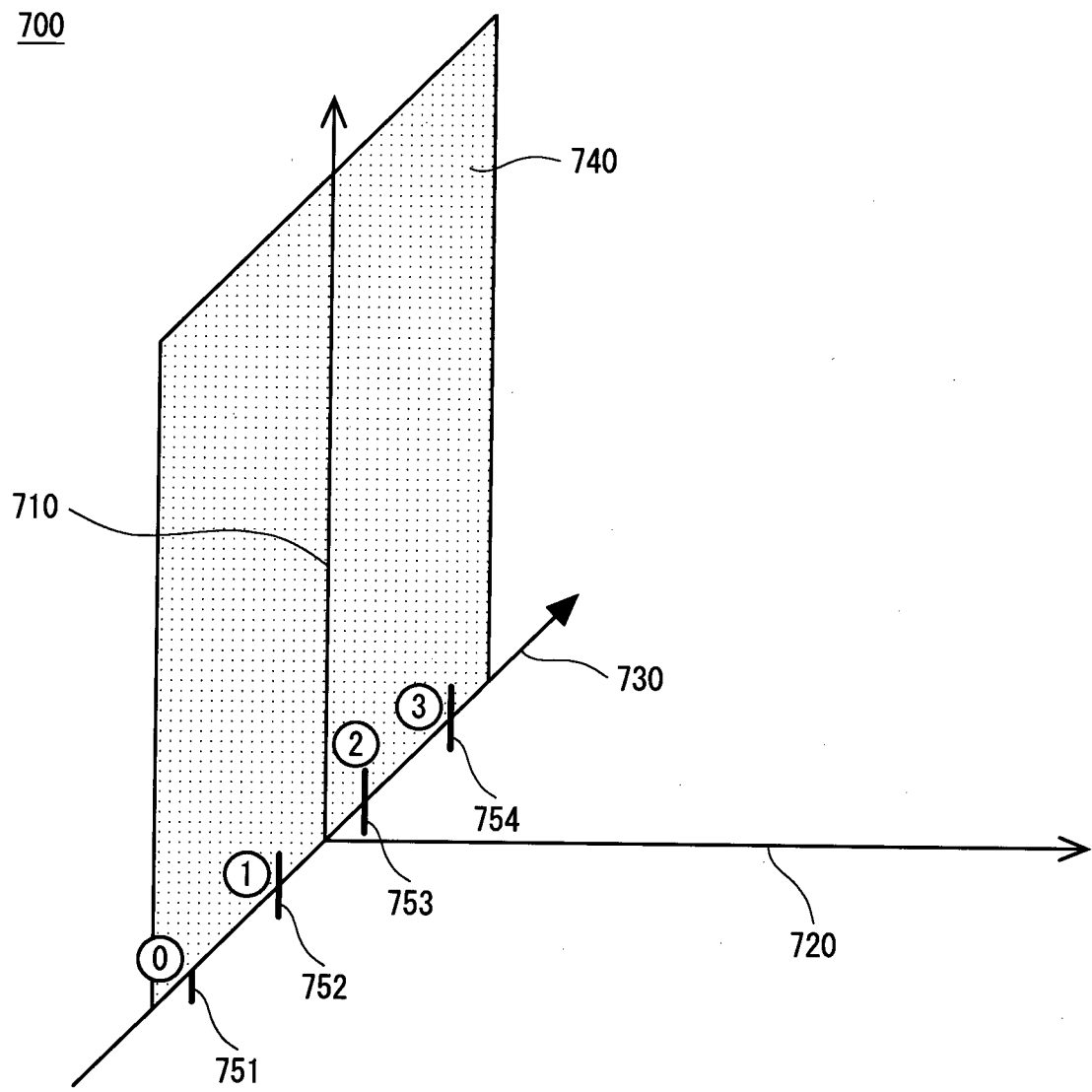
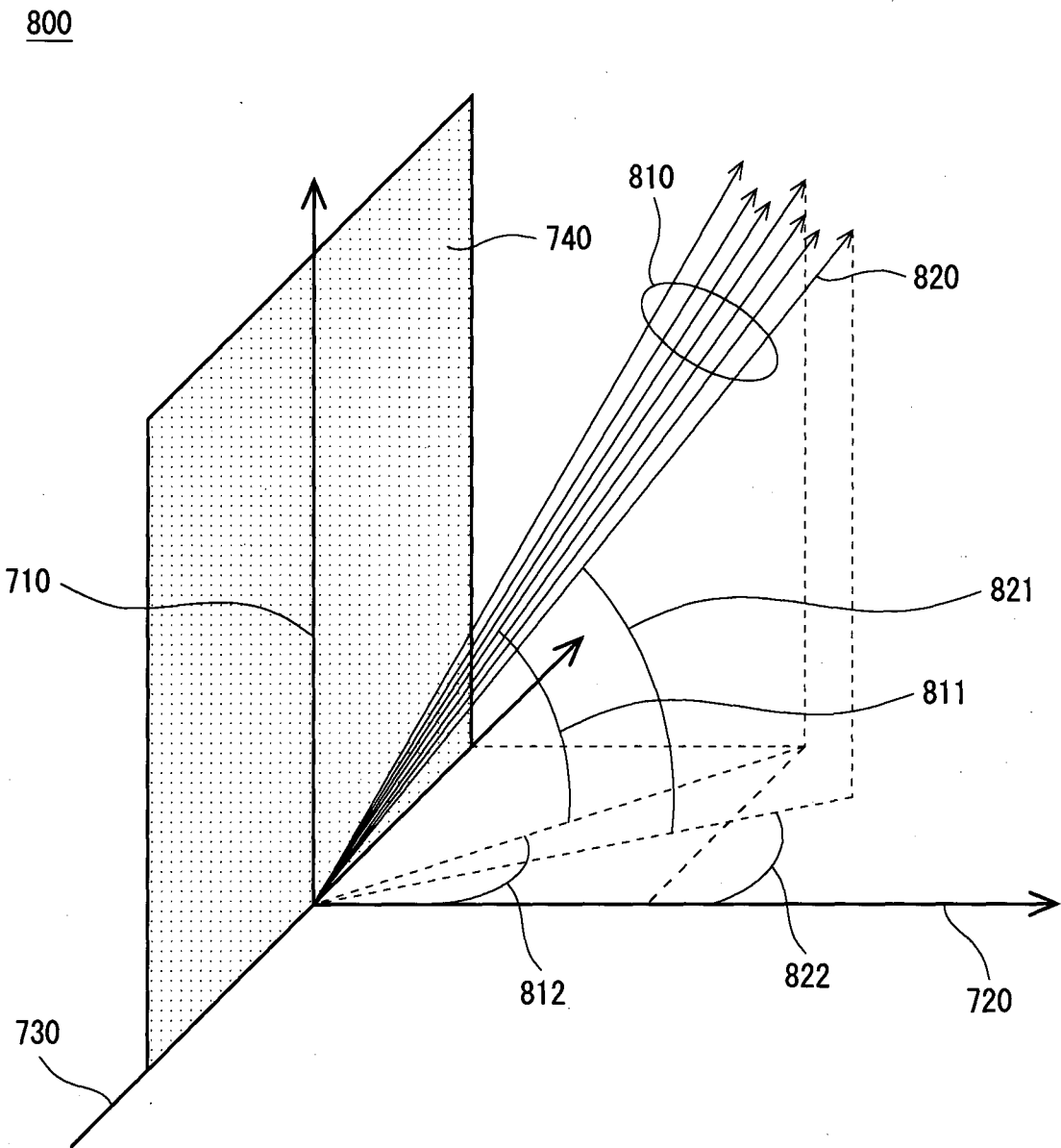


Fig. 8



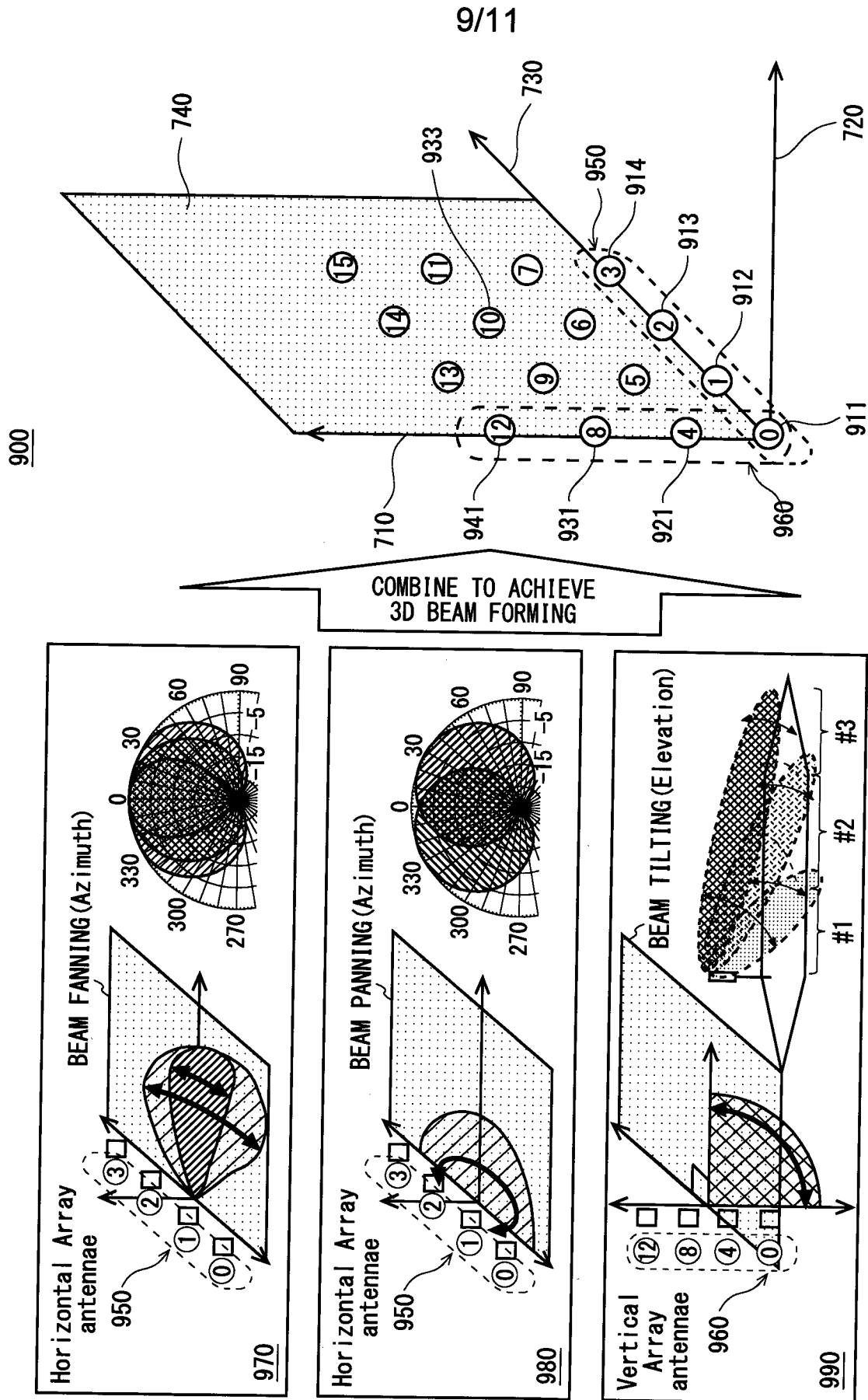
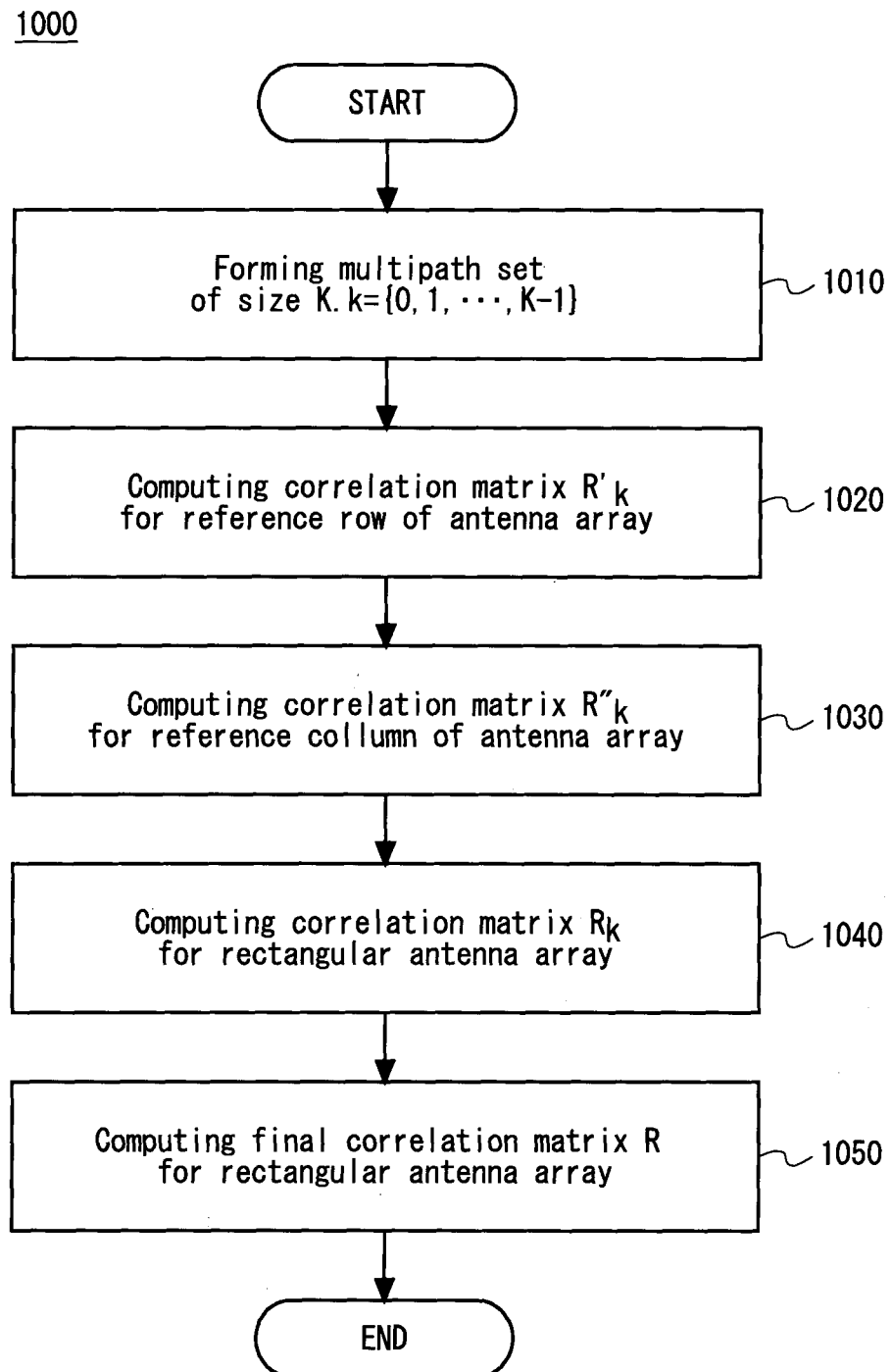


Fig. 9

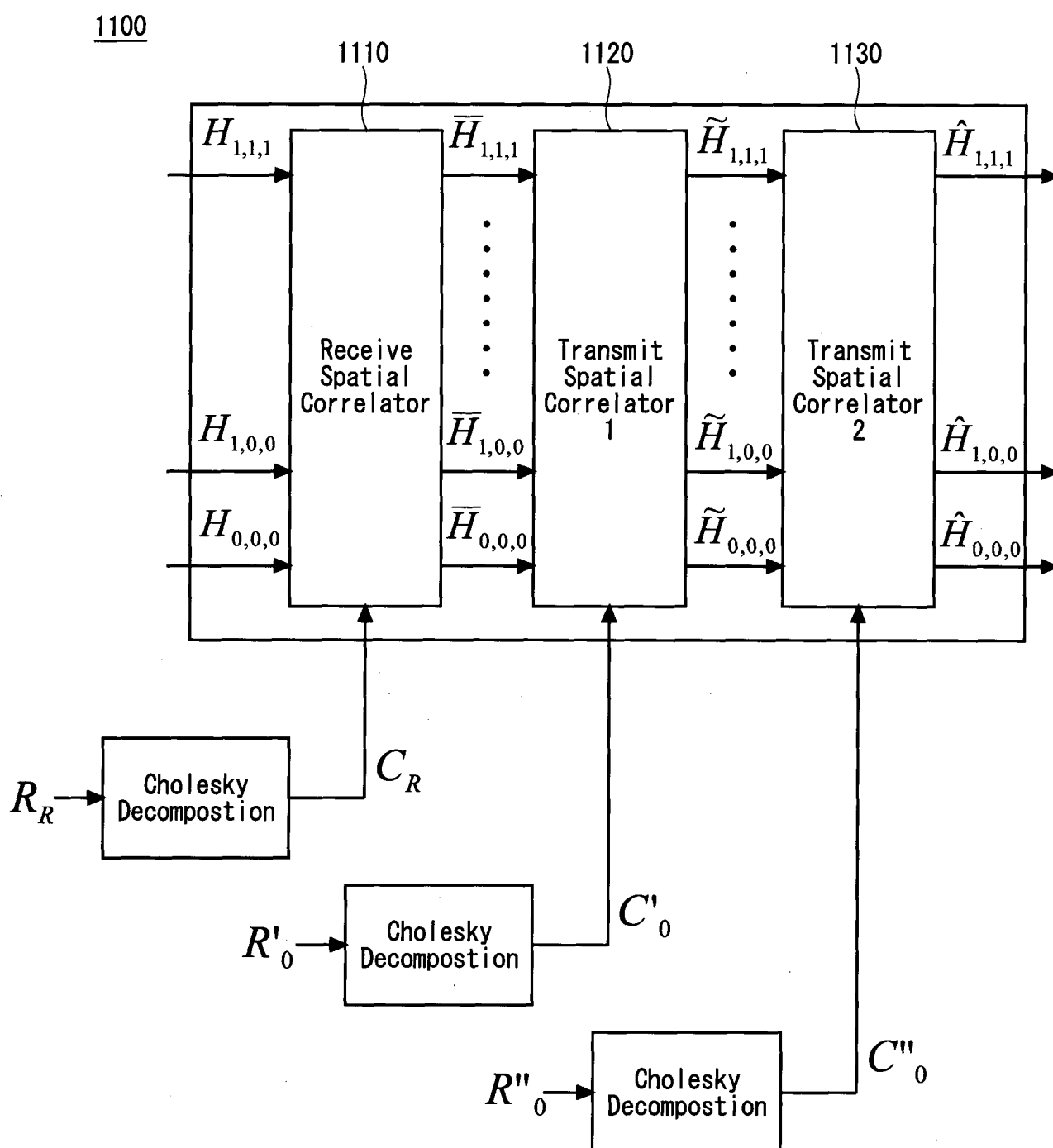
10/11

Fig. 10



11/11

Fig. 11



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2014/070285

A. CLASSIFICATION OF SUBJECT MATTER		
Int.Cl. H04W24/06(2009.01)i, H04B7/10(2006.01)i, H04J99/00(2009.01)i, H04W16/28(2009.01)i		
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)		
Int.Cl. H04W4/00-99/00, H04B7/10, H04J99/00		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Published examined utility model applications of Japan 1922-1996 Published unexamined utility model applications of Japan 1971-2014 Registered utility model specifications of Japan 1996-2014 Published registered utility model applications of Japan 1994-2014		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	NTT DOCOMO, Views on 3D-Channel Model for Elevation Beamforming and FD-MIMO, 3GPP TSG RAN WG1 Meeting #72, R1-130410, 2013.02.01 Full text; all drawings	1-22
A	NEC GROUP, On the 4TX Codebook Enhancement, 3GPP TSG RAN WG1 Meeting #72, R1-130845, 2013.02.01 Full text; all drawings	1-22
☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.		
* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 22.08.2014		Date of mailing of the international search report 02.09.2014
Name and mailing address of the ISA/JP Japan Patent Office 3-4-3, Kasumigaseki, Chiyoda-ku, Tokyo 100-8915, Japan		Authorized officer Masayuki TAKAHASHI Telephone No. +81-3-3581-1101 Ext. 3534

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2014/070285

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CATR, Consideration on how to extend ITU-R channel models to 3D, 3GPP TSG RAN WG1 Meeting #72bis, R1-131513, 2013.04.20 Full text; all drawings	1-22
A	SHAFI, M., ET.AL., Polarized MIMO Channels in 3-D: Models, Measurements and Mutual Information, IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, 2006.03, Vol.24, No.3, pp.514-527 chapter IV.B	1-22