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SYSTEM AND METHOD FOR TRANSMITTING RADIO FREQUENCY RADIATION

TECHNOLOGICAL FIELD

The present invention relates to antenna arrays, and more particularly to techniques for transmitting radio frequency (RF) radiation in a predetermined direction within a predetermined frequency band by an antenna array.

5 BACKGROUND

A phased array antenna is an electronically controlled array of multiple antenna elements which operate together to transmit or receive electro-magnetic radiation. The phased array generates an electro-magnetic radiation beam that can be electronically steered to a desired direction(s) without physically moving the antenna elements. In
10 operation, the electro-magnetic waves, radiated by each antenna element, combine and superpose (i.e., interfering constructively) to enhance the power of the beam radiated in desired direction(s), while suppressing and reducing the power of radiation (i.e. interfering destructively) in other undesired directions.

In a phased array, each antenna element is fed with a signal provided by a steering
15 system. The steering system includes a plurality of phase shifters and amplifiers, which are typically controlled by a computer system that can alter the phase and amplitude of the signal electronically, thereby steering the beam of the phased array antenna to the desired direction(s).

Usually, when antenna arrays operate at a frequency range of up to 3 octaves, for
20 example: 2-6 GHz, 6-18 GHz, etc. (i.e., when the maximum frequency of the range is up to 3 times the lower frequency), “null points” may appear in the gain diagram at certain frequencies beyond this range due to mutual coupling between the antenna elements of the phased array. Null points occur at the frequencies at which the amount of transmitted energy is less than a certain value. At these null points, some part of the energy is reflected

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back to the system from the antenna elements that may cause severe damage to the system.

One reason for mutual coupling between the antenna elements stems from reflection, diffraction and scattering of the radiation, thus causing interchange of energy
5 between the antenna elements.

Another reason for mutual coupling is due to the fact that a part of the phase shifted current, which is directed to a certain antenna element, may reach other neighboring antenna elements. Accordingly, the currents are not fully radiated by the corresponding antenna elements, which can result in decrease of the efficiency of the
10 radiating elements.

In phased array antenna systems, the operation frequency bandwidth is determined by the distance between the antenna elements of the phased array system, while the gain is determined by the number of antenna elements in the phased array system.

15 **GENERAL DESCRIPTION**

Prior art phased array antenna systems suffer from several drawbacks since the frequency bandwidth in such systems can only be tailored by changing the structural parameters of the system, i.e., changing the distance between the antenna elements of the phased array antenna. Another drawback is the fact that some of the energy is transmitted
20 in undesired directions, thereby forming sidelobes. Accordingly, the gain in the direction of interest can be decreased.

Thus, there is still a need in the art for, and it would be useful to have, a novel system for operating the phased array system at frequencies outside the predetermined bandwidth of transmission of the phased array system without changing the structural
25 parameters of this system.

It would be advantageous to have a phased array system that can provide a high antenna gain, while attenuating the reflected energy at the null points.

The present invention addresses the deficiencies of conventional phased array systems, and provides a novel transmission system for transmitting radio frequency (RF)
30 radiation in a predetermined direction at a sequence of K frequencies selected from a predetermined frequency range by an antenna array that comprises a predetermined number

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N of antenna elements. It should be noted that the predetermined frequency range can include null points that occur at certain frequencies within the predetermined frequency range.

According to an embodiment of the present invention, the transmission system includes an RF signal generator. The RF signal generator is configured for generating
5 electrical signals at a sequence of K frequencies. Each electrical signal has an initial amplitude and an initial phase. In operation, the electrical signals are relayed to the phased antenna array at the sequence of K frequencies through N transmission channels corresponding to the N antenna elements.

According to an embodiment, the transmission system also includes a
10 modification system arranged downstream of the RF signal generator. In the present application, an arrangement of one element downstream of another element implies electrical coupling of these elements to each other with a possibility to transfer electrical signals between the elements in the direction of the current associated with the transferring of the electrical signals.

15 The modification system is configured for receiving and processing the electrical signals from the RF signal generator for obtaining optimal electrical signals. In the present application, the optimal electrical signals refer to the electrical signals for which a transmission efficiency coefficient of the transmission system is equal to or greater than a predetermined threshold value. In particular, the optimal electrical signals include
20 optimal unmodified signals provided by the RF signal generator and optimal modified signals generated by the modification system.

According to an embodiment, the transmission system also includes a steering system arranged downstream of said modification system and coupled to said antenna array. The steering system is configured for receiving the optimal electrical signals
25 obtained from the modification system and generating steering electrical signals related to the optimal electrical signals. The steering electrical signals are relayed via the N transmission channels to the antenna array to form a steered beam for transmission in the predetermined direction.

According to an embodiment, the modification system includes an efficiency
30 determination unit. The efficiency determination unit is configured for receiving the electrical signals at the sequence of K frequencies from the RF signal generator and for calculating the transmission efficiency coefficient of the transmission system for each k -th frequency f_k .

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According to an embodiment, the modification system also includes a comparing unit. The comparing unit is configured for receiving the transmission efficiency coefficient for each k -th frequency f_k from the efficiency determination unit and comparing the transmission efficiency coefficient with the predetermined threshold value.

5 The modification system is also configured for separating electrical signals corresponding to the frequencies for which the transmission efficiency coefficient is less than the predetermined threshold value, from the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient is equal to or greater than the predetermined threshold value. In operation, the modification system provides the

10 electrical signals corresponding to the frequencies for which the transmission efficiency coefficient is equal to or greater than the predetermined threshold value to the steering system.

According to an embodiment, the modification system further includes a randomization unit. The randomization unit is configured for receiving the electrical

15 signals corresponding to the frequencies for which the transmission efficiency coefficient is less than a predetermined threshold value, and iteratively modifying these electrical signals by randomizing amplitude and phase of these electrical signals, thereby generating randomized signals. Each randomized signal has a corresponding randomized amplitude and randomized phase. In operation, the modification system provides in each iteration

20 the randomized signals to the efficiency determination unit to calculate transmission efficiency coefficient for the randomized signals.

It should be noted that null-points can occur at one or more frequencies within the sequence of K frequencies. The transmission efficiency coefficient for the electrical signals which correspond to these frequencies (at which null points can occur) is below

25 the predetermined threshold value. The modification system receives and iteratively modifies these electrical signals until the transmission efficiency coefficient for these electrical signals is equal to or greater than the predetermined threshold value. As a result of the iterative modification of these electrical signals, the null points are removed.

According to an embodiment, the optimal modified signals are the randomized

30 signals for which the transmission efficiency coefficient is equal to or greater than the predetermined threshold value. Likewise, the optimal unmodified signals are electrical signals for which the transmission efficiency coefficient is equal to or greater than the

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predetermined threshold value. It should be noted that the optimal unmodified signals are electrical signals which have the initial amplitude and the initial phase.

According to an embodiment, the randomization system is configured for performing iterative modification of the electrical signals corresponding to the
5 frequencies for which the transmission efficiency coefficient is less than the predetermined threshold value. The iterative modification is performed until the transmission efficiency coefficient for these electrical signals is equal to or greater than the predetermined threshold value.

According to an embodiment, the transmission efficiency coefficient is calculated
10 by:

$$T_k = \frac{E_{trans}}{E_{total}} \cdot 100\% ,$$

where E_{total} is the total energy of the electrical signals for the k -th frequency f_k generated by the RF signal generator and E_{trans} is the energy transmitted in operation for the k -th frequency f_k .

15 According to an embodiment, the transmitted energy E_{trans} is calculated by the efficiency determination unit by using the relationship $E_{trans} = E_{total} - E_{lost}$, where E_{lost} is the energy that is lost by the transmission system in operation for the k -th frequency f_k .

According to an embodiment, the lost energy E_{lost} is calculated by:

$$E_{lost} = \sum_{n=1}^N |\tilde{s}|_n ,$$

20 where $\tilde{s}_n$ is a combined energy that an n -th antenna element ($n = 1, 2, \dots, N$) in the antenna array receives from neighboring antenna elements and a self-reflected energy of the n -th antenna element.

According to an embodiment, the combined energy $\tilde{s}_n$ is calculated by:

$$\begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \\ \tilde{s}_3 \\ \vdots \\ \tilde{s}_N \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} & s_{13} & \cdots & s_{1N} \\ s_{21} & s_{22} & s_{23} & \cdots & s_{2N} \\ s_{31} & s_{32} & s_{33} & \cdots & s_{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ s_{N1} & s_{N2} & \cdots & s_{N3} & \cdots & s_{NN} \end{pmatrix} \cdot \begin{pmatrix} A_1 e^{j\varphi_1} \\ A_2 e^{j\varphi_2} \\ A_3 e^{j\varphi_3} \\ \vdots \\ A_N e^{j\varphi_N} \end{pmatrix},$$

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where $V_k^{init} = \begin{pmatrix} A_1 e^{j\varphi_1} \\ A_2 e^{j\varphi_2} \\ A_3 e^{j\varphi_3} \\ \vdots \\ A_N e^{j\varphi_N} \end{pmatrix}_k$ is an initial excitation vector representing the electrical

signals for N transmission channels for each k -th frequency f_k , and

$S = \begin{pmatrix} S_{11} & S_{12} & S_{13} & \cdots & S_{1N} \\ S_{21} & S_{22} & S_{23} & \cdots & S_{2N} \\ S_{31} & S_{32} & S_{33} & \cdots & S_{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ S_{N1} & S_{N2} & \cdots & S_{NN} \end{pmatrix}$ is a coupling matrix characterizing mutual coupling

between antenna elements and a self-reflected energy of the antenna elements in the
5 antenna array.

According to an embodiment, the transmitted energy E_{trans} of the transmission system is calculated by:

$$E_{trans} = E_{total} - E_{lost} = \sum_{n=1}^N |A_n e^{j\varphi_n}| - \sum_{n=1}^N |\widetilde{s}|_n$$

According to an embodiment, the randomizing of the amplitude and the phase of
10 the electrical signals is carried out by iteratively generating two random numbers. Each random number is in the interval $[0, 1]$. The initial amplitude and the initial phase of the electrical signals are multiplied by these two random numbers, correspondingly, thereby generating the randomized signals.

According to an embodiment, the two random numbers are different for each
15 electrical signal in an n -th transmission channel ($n = 1, 2, \dots, N$).

According to an embodiment, the randomization system further includes an optimal efficiency determination system. The optimal efficiency determination system is arranged downstream of the randomization unit and coupled to the comparing unit and to the efficiency determination unit.

According to an embodiment, the optimal efficiency determination system is
20 configured for sub-iteratively modifying the two random numbers, thereby generating in each sub-iteration two modified random numbers. The optimal efficiency determination system is also configured for generating modified randomized signals for which the transmission efficiency coefficient is greater than the transmission efficiency coefficient
25 of the randomized signals by using the two modified random numbers.

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According to an embodiment, the optimal efficiency determination system is configured to perform a predetermined number P of sub-iterations to generate the modified randomized signals for which the transmission efficiency coefficient is greater than the transmission efficiency coefficient of the randomized signals provided by the randomization unit.

According to an embodiment, the optimal efficiency determination system includes a modification unit. The modification unit is configured for receiving the electrical signals for which the transmission efficiency coefficient is less than the predetermined threshold value from the comparing unit. The modification unit also receives the corresponding two random numbers for each electrical signal from the randomization unit. The modification unit is also configured for sub-iteratively modifying the electrical signals, thereby generating the modified randomized signals.

The optimal efficiency determination system also includes an efficiency determination sub-unit arranged downstream of the modification unit. The efficiency determination sub-unit is configured for sub-iteratively receiving in each sub-iteration the modified randomized signals from the modification unit and calculating a transmission efficiency coefficient for these modified randomized signals.

The optimal efficiency determination system further includes a storing unit configured for storing the transmission efficiency coefficient for the modified randomized signals and a corresponding excitation vector sub-iteratively received from the efficiency determination sub-unit. The storing unit is also configured for storing the transmission efficiency coefficient for the randomized signals, and a corresponding randomized vector that is iteratively obtained (i.e., obtained in each iteration of the modification system) from the efficiency determination unit.

The optimal efficiency determination system also includes a comparing sub-unit coupled to the storing unit. The comparing sub-unit is configured for sub-iteratively receiving a stored efficiency coefficient from the storing unit and the transmission efficiency coefficient for the modified randomized signals from the efficiency determination sub-unit. The comparing sub-unit is also configured for sub-iteratively comparing the stored efficiency coefficient with the transmission efficiency coefficient of the modified randomized signals. The comparing sub-unit is also configured for providing the transmission efficiency coefficient for the modified randomized signals and the corresponding excitation vector to the storing unit for storing thereof when the value

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of this transmission efficiency coefficient for the modified randomized signals is greater than the value of said stored efficiency coefficient.

According to an embodiment, the modification of the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient is less
5 than the predetermined threshold value by the modification unit is carried out by multiplying the initial amplitude and the initial phase of each electrical signal by two modified random numbers, correspondingly.

According to an embodiment, the two modified random numbers are generated sub-iteratively by adding $\pm A\beta_1 \cdot p$ and $\pm A\beta_2 \cdot p$ to the two random numbers,
10 correspondingly, where $p = 1, 2, \dots, P$.

According to another general aspect of the present invention, there is provided a method for transmitting radio frequency (RF) radiation in a predetermined direction at a sequence of K frequencies by an antenna array comprising a predetermined number N of antenna elements.

15 The method includes generating electrical signals having an initial amplitude and an initial phase at a sequence of K frequencies. The method also includes processing the electrical signals and obtaining optimal electrical signals for which the transmission efficiency coefficient is equal to or greater than a predetermined threshold value. The optimal electrical signals include optimal unmodified signals and optimal modified
20 signals. According to an embodiment, the method also includes generating steering electrical signals related to the optimal electrical signals. Then, the method includes forming a steered beam based on the steering electrical signals for transmission in the predetermined direction.

According to another embodiment of the present invention, there is provided a
25 method for the obtaining of the optimal electrical signals. The method includes calculating a transmission efficiency coefficient for each k -th frequency f_k of the sequence of K frequencies; The method also includes comparing the transmission efficiency coefficient for each k -th frequency f_k with a predetermined threshold value.

According to an embodiment, the method also includes separating electrical
30 signals corresponding to the frequencies for which the transmission efficiency coefficient is less than the predetermined threshold value, from the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient is equal to or greater than the predetermined threshold value.

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According to an embodiment, the method also includes iteratively modifying the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient is less than a predetermined threshold value. The iterative modification of these electrical signals is carried out by randomizing amplitude and phase of these electrical signals, thereby generating randomized signals. Then, the method also includes providing optimal electrical signals including optimal unmodified signals and optimal modified signals.

According to an embodiment, the optimal modified signals are the randomized signals for which the transmission efficiency coefficient is equal to or greater than the predetermined threshold value, and the optimal unmodified signals are the electrical signals having said initial amplitude and said initial phase for which the transmission efficiency coefficient is equal to or greater than the predetermined threshold value.

According to an embodiment, the iterative modifying of the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient is less than the predetermined threshold value is performed until the transmission efficiency coefficient for these electrical signals is equal to or greater than the predetermined threshold value, thereby generating the optimal modified signals.

According to an embodiment, the transmission efficiency coefficient is calculated by:

$$T_k = \frac{E_{trans}}{E_{total}} \cdot 100\% \quad ,$$

where E_{total} is the total energy of the electrical signals for the k -th frequency f_k . E_{trans} is the energy transmitted in operation for the k -th frequency f_k calculated by $E_{trans} = E_{total} - E_{lost}$, where E_{lost} is the energy that is lost in operation for the k -th frequency f_k .

According to an embodiment, the lost energy E_{lost} is calculated by:

$$E_{lost} = \sum_{n=1}^N |\tilde{s}|_n$$

where $\tilde{s}_n$ is a combined energy that an n -th antenna element in the antenna array (14) receives from neighboring antenna elements and a self-reflected energy of the n -th antenna element.

According to an embodiment, the combined energy $\tilde{s}_n$ is calculated by:

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$$\begin{pmatrix} \widetilde{s}_1 \\ \widetilde{s}_2 \\ \widetilde{s}_3 \\ \vdots \\ \widetilde{s}_N \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} & s_{13} & \cdots & s_{1N} \\ s_{21} & s_{22} & s_{23} & \cdots & s_{2N} \\ s_{31} & s_{32} & s_{33} & \cdots & s_{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ s_{N1} & s_{N2} & \cdots & s_{N3} & \cdots & s_{NN} \end{pmatrix} \cdot \begin{pmatrix} A_1 e^{j\varphi_1} \\ A_2 e^{j\varphi_2} \\ A_3 e^{j\varphi_3} \\ \vdots \\ A_N e^{j\varphi_N} \end{pmatrix},$$

where $V_k^{init} = \begin{pmatrix} A_1 e^{j\varphi_1} \\ A_2 e^{j\varphi_2} \\ A_3 e^{j\varphi_3} \\ \vdots \\ A_N e^{j\varphi_N} \end{pmatrix}_k$ is an initial excitation vector representing the electrical

signals for N transmission channels for each k -th frequency f_k and

$S = \begin{pmatrix} s_{11} & s_{12} & s_{13} & \cdots & s_{1N} \\ s_{21} & s_{22} & s_{23} & \cdots & s_{2N} \\ s_{31} & s_{32} & s_{33} & \cdots & s_{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ s_{N1} & s_{N2} & \cdots & s_{N3} & \cdots & s_{NN} \end{pmatrix}$ is a coupling matrix characterizing mutual coupling

- 5 between antenna elements and the self-reflected energy of the antenna elements in the antenna array (14).

According to an embodiment, the transmitted energy E_{trans} of the transmission system is calculated by:

$$E_{trans} = E_{total} - E_{lost} = \sum_{n=1}^N |A_n e^{j\varphi_n}| - \sum_{n=1}^N |\widetilde{s}|_n$$

- 10 According to an embodiment, randomizing the amplitude and the phase of the electrical signals is carried out by iteratively generating two random numbers. Each random number is in the interval $[0, 1]$. The initial amplitude and the initial phase of the electrical signals are multiplied by the two random numbers, correspondingly, thereby generating the randomized signal. The two random numbers can be different for each
- 15 electrical signal in an n -th transmission channel selected from the N transmission channels.

- According to an embodiment, iterative modifying of the electrical signals further includes providing modified randomized signals for which the transmission efficiency coefficient is greater than the transmission efficiency coefficient of the randomized
- 20 signals.

According to another general aspect of the present invention, there is provided a method for providing modified randomized signals for which the transmission efficiency

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coefficient is greater than the transmission efficiency coefficient of the randomized signals.

According to an embodiment, the method includes receiving and storing the transmission efficiency coefficient of the randomized signals and a corresponding
5 randomized excitation vector. The method also includes sub-iteratively modifying the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient is less than the predetermined threshold value, thereby generating the modified randomized signals. The method also includes sub-iteratively calculating a transmission
10 efficiency coefficient for these modified randomized signals. The method also includes sub-iteratively comparing the transmission efficiency coefficient for the modified randomized signals with a previously stored transmission efficiency coefficient. The method also includes sub-iteratively replacing the previously stored transmission efficiency coefficient and the previously stored randomized excitation vector with the
15 transmission efficiency coefficient for the modified randomized signals and a corresponding modified excitation vector when the transmission efficiency coefficient for the modified randomized signals is greater than the previously stored transmission efficiency coefficient.

According to an embodiment, the providing of the modified randomized signals for which the transmission efficiency coefficient is greater than the transmission
20 efficiency coefficient of the randomized signals is carried out by performing a predetermined number P of sub-iterations.

According to an embodiment, the sub-iterative modifying of the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient is less than the predetermined threshold value is carried out by multiplying the initial amplitude
25 and initial phase of each electrical signal by corresponding two modified random numbers.

According to an embodiment, said two modified random numbers are generated by sub-iteratively adding $\pm A\beta_1 \cdot p$ and $\pm A\beta_2 \cdot p$ to the two random numbers, correspondingly, where $p = 1, 2, \dots, P$.

30 There has thus been outlined, rather broadly, the more important features of the invention in order that the detailed description thereof that follows hereinafter may be better understood. Additional details and advantages of the invention will be set forth in the

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detailed description, and in part will be appreciated from the description, or may be learned by practice of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to better understand the subject matter that is disclosed herein and to
5 exemplify how it may be carried out in practice, embodiments will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

Fig. 1 illustrates a schematic block diagram of a transmission system configured for transmitting RF radiation in a predetermined direction at a sequence of K frequencies
10 within a predetermined frequency band, according to an embodiment of the present invention;

Fig. 2 illustrates a schematic flow-chart diagram of a method of operation of a transmission system in **Fig. 1**, according to an embodiment of the present invention;

Fig. 3 illustrates a schematic block diagram of a transmission system configured
15 for transmitting RF radiation in a predetermined direction at a sequence of K frequencies within a predetermined frequency band, according to another embodiment of the present invention;

Fig. 4 illustrates a schematic flow-chart diagram of a method of operation of a transmission system in **Fig. 3**, according to an embodiment of the present invention;

20 **Fig. 5** illustrates a schematic flow-chart diagram of a method for providing modified randomized signals, according to an embodiment of the present invention;

Fig. 6 illustrates an example of the frequency dependence of the transmitted energy of the transmission system shown in **Fig. 3** and the frequency dependence of the transmitted energy of a conventional system, which does not include the modification
25 system; and

Figs. 7A and 7B illustrate an example of a radiation azimuth pattern generated by the transmission system shown in **Fig. 3** and a radiation azimuth pattern generated by a conventional system which does not include the modification system at two different frequencies, correspondingly.

DETAILED DESCRIPTION OF EMBODIMENTS

The principles and operation of the transmission system and method for transmitting RF radiation in a predetermined direction at a sequence of K frequencies within a predetermined frequency band according to the present invention may be better understood with reference to the drawings and the accompanying description, it being understood that these drawings and examples in the description are given for illustrative purposes only and are not meant to be limiting. The same reference Roman numerals and alphabetic characters will be utilized for identifying those components which are common in the transmission system and its components shown in the drawings throughout the present description of the invention. It should be noted that the blocks in the drawings illustrating various embodiments of the present invention are intended as functional entities only, such that the functional relationships between the entities are shown, rather than any physical connections and/or physical relationships.

Some portions of the detailed descriptions, which follow hereinbelow, are presented in terms of algorithms and/or symbolic representations of operations on data represented as physical quantities within registers and memories of a computer system. An algorithm is here conceived to be a sequence of steps requiring physical manipulations of physical quantities and leading to a desired result. Usually, although not necessarily, these quantities take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated. In the present description, these signals can be referred to as values, elements, symbols, terms, numbers, or the like.

Unless specifically stated otherwise, throughout the description, utilizing terms such as "computing" or "calculating" or "determining" or "obtaining" or the like, refer to the action and processes of a computer system, or similar electronic processing device, that manipulates and transforms data.

Referring to **Fig. 1**, a schematic block diagram of a transmission system **10** for transmitting radio frequency (RF) radiation in a predetermined direction at a sequence of K frequencies within a predetermined frequency band is illustrated, according to an embodiment of the present invention.

The transmission system **10** includes an RF generator **11**, a randomization system **12** arranged downstream of the RF signal generator **11**, a steering system **13** arranged downstream of the modification system **12** and an antenna array **14** comprising a plurality of N antenna elements coupled to the steering system **13**.

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In the present application, an arrangement of one element downstream of another element implies electrical coupling of these elements to each other with a possibility to transfer electrical signals between the elements in the direction of the current associated with the transferring of the electrical signals.

5 The RF generator **11** is configured and operable for generating electrical signals through N transmission channels, corresponding to N antenna elements, for each frequency of the sequence of K frequencies $f_1, f_2, \dots, f_K$ within the predetermined frequency band. The number N of the transmission channels is equal to the predetermined number of antenna elements in the antenna array **14**. In other words, the RF generator **11**
 10 can generate electrical signals for each k -th frequency f_k (where $k = 1, 2, \dots, K$) of the sequence of K frequencies $f_1, f_2, \dots, f_K$. Each electrical signal has a corresponding initial amplitude A and an initial phase φ .

For each transmission channel, electrical signals generated by the RF generator **11** for the k -th frequency f_k can be represented by the expression $A_k e^{-j(2\pi f_k t + \varphi_k)}$, where
 15 A_k is the initial amplitude of this signal, and φ_k is the initial phase of this signal.

For N transmission channels for each k -th frequency f_k of the sequence of K frequencies $f_1, f_2, \dots, f_K$, the electrical signals can be represented by an initial excitation vector V_k^{init} having N vector elements:

$$V_k^{init} = \begin{pmatrix} A_1 e^{j\varphi_1} \\ A_2 e^{j\varphi_2} \\ A_3 e^{j\varphi_3} \\ \vdots \\ A_N e^{j\varphi_N} \end{pmatrix}_k$$

20 The vector elements $A_n e^{j\varphi_n}$ ($n = 1, 2, \dots, N$) relate to the corresponding electrical signals of the k -th frequency f_k in the corresponding transmission channel. In particular, each vector element in the initial excitation vector V_k^{init} includes the initial amplitude A_n and initial phase φ_n of the corresponding electrical signals for the k -th frequency f_k .

According to an embodiment, the modification system **12** is configured for
 25 receiving and processing the electrical signals corresponding to the N transmission channels for each k -th frequency f_k from the RF signal generator **11**. The modification system **12** is also configured for relaying optimal electrical signals associated with transmission efficiency coefficients greater than a predetermined threshold value to the steering system **13** as described hereinbelow. The optimal electrical signals include

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optimal unmodified signals provided by the RF signal generator **11** and optimal modified signals generated by the modification system **12** during operation, as also described hereinbelow.

In operation, the modification system **12** calculates a transmission efficiency coefficient T_k of the transmission system **10** for each k -th frequency f_k of the sequence of K frequencies $f_1, f_2, \dots, f_K$ within the predetermined frequency band, and compares the transmission efficiency coefficient T_k with a predetermined threshold value X . More specifically, the modification system **12** receives the corresponding excitation vector for each k -th frequency f_k of the sequence of K frequencies $f_1, f_2, \dots, f_K$, and utilizes the excitation vector for calculating the transmission efficiency coefficient T_k of the transmission system **10** for each k -th frequency f_k as described in further detail below.

According to an embodiment, the modification system **12** is also configured for separating electrical signals corresponding to the frequencies for which the transmission efficiency coefficient T_k is less than the predetermined threshold value X from the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient T_k is equal to or greater than the predetermined threshold value X .

According to an embodiment, the modification system **12** is also configured for providing the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient T_k is equal to or greater than the predetermined threshold value X to the steering system **13**. In other words, the modification system **12** provides the electrical signals through the N transmission channels for each frequency for which the transmission efficiency coefficient T_k is equal to or greater than the predetermined threshold value X to the steering system **13**. For example, the threshold value X can be in the range of 70% - 90%.

Electrical signals having the initial amplitude and the initial phase received from the RF signal generator, which correspond to the frequencies for which the transmission efficiency coefficient T_k is equal to or greater than the predetermined threshold X value and which are provided to the steering system **13** are referred to herein as "optimal unmodified signals".

According to an embodiment, the modification system **12** is configured to perform iterative modification of the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient T_k is less than the predetermined threshold value X . Specifically, in each iteration, the modification system **12** modifies

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these electrical signals by randomizing amplitude and phase of these electrical signals, thereby generating randomized signals. The modification system **12** is also configured for calculating updated transmission efficiency coefficient $T_{ran,k}$ for the randomized signals and for comparing this $T_{ran,k}$ with the predetermined threshold value X in each iteration. The iterative modification is performed until the transmission efficiency coefficient T_k for these randomized signals is equal to or greater than the predetermined threshold value X . As a result of the iterative modification, the transmission efficiency coefficient $T_{ran,k}$ for the randomized signals is greater than the predetermined threshold value X .

It should be noted that null-points can occur at one or more frequencies within the sequence of K frequencies. The transmission efficiency coefficient T_k for the electrical signals which correspond to these frequencies (at which null points can occur) is below the predetermined threshold value X . The modification system **12** receives and iteratively modifies these electrical signals until the transmission efficiency coefficient T_k for these electrical signals is equal to or greater than the predetermined threshold value X . As a result of the iterative modification of these electrical signals, the null points are removed.

The randomized signals for which the transmission efficiency coefficient $T_{ran,k}$ is greater than the predetermined threshold value X are referred to herein as "optimal modified signals".

The modification system **12** is configured to relay optimal electrical signals, which include the optimal unmodified signals (obtained from the RF signal generator **11**), and the optimal modified signals (obtained from the modification system **12**) to the steering system **13**.

According to an embodiment, the steering system **13** processes the optimal electrical signals and forms a steered beam of the RF radiation to the predetermined direction. The steering system **13** relays the electrical signals corresponding to the steered beam to the antenna array **14** for transmission.

According to an embodiment, the modification system **12** includes an efficiency determination unit **22**, a comparing unit **24** arranged downstream of the efficiency determination unit **22**, and a randomization unit **26** arranged downstream of the comparing unit **24**.

According to an embodiment, the efficiency determination unit **22** is configured to receive the electrical signals for each k -th frequency f_k of the sequence of K frequencies

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$f_1, f_2, \dots, f_K$, to process these electrical signals, and to calculate for each k -th frequency f_k the transmission efficiency coefficient T_k of the transmission system **10**. The transmission efficiency coefficient T_k represents the amount of energy transmitted by the transmission system **10** for each k -th frequency f_k of the sequence of K frequencies $f_1, f_2, \dots, f_K$. More specifically, each k -th frequency f_k has a corresponding transmission efficiency coefficient T_k associated therewith.

According to an embodiment, the transmission efficiency coefficient T_k can be calculated by:

$$T_k = \frac{E_{trans}}{E_{total}} \cdot 100\% \quad , \quad (1)$$

where E_{total} is the total energy of the electrical signals for the k -th frequency f_k generated by the RF signal generator **11**, and E_{trans} is the energy transmitted by the transmission system **10** in operation for the k -th frequency f_k .

More specifically, E_{trans} can be calculated by the efficiency determination unit **22** by using a relationship $E_{trans} = E_{total} - E_{lost}$, where E_{lost} is the energy that is lost by the transmission system **10** in operation for the k -th frequency f_k .

In particular, E_{lost} is the energy that the transmission system **10** loses due to the mutual coupling between the antenna elements and the self-reflected energy of the antenna elements in the antenna array **14** when operating at the k -th frequency f_k .

According to an embodiment, the lost energy E_{lost} of the transmission system **10** can be determined by taking into account the mutual coupling between the antenna elements, i.e., the amount of energy that each antenna element in the antenna array **14** receives from the neighboring antenna elements and the self-reflected energy of the antenna elements, and then summing the energies for all the antenna elements.

The mutual coupling between the antenna elements and the self-reflected energy of the antenna elements in the antenna array **14** are characterized by a coupling matrix S . For the antenna array **14** that includes N antenna elements, the coupling matrix S is a $N \times N$ matrix:

$$S = \begin{pmatrix} S_{11} & S_{12} & S_{13} & \cdots & S_{1N} \\ S_{21} & S_{22} & S_{23} & \cdots & S_{2N} \\ S_{31} & S_{32} & S_{33} & \cdots & S_{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ S_{N1} & S_{N2} & \cdots & S_{NN} & \end{pmatrix}$$

Each non-diagonal coupling coefficient of the coupling matrix S represents the energy received by the corresponding antenna element from the neighboring antenna

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elements. For example, s_{1_2} is the energy received by the 1st antenna element from the 2nd neighboring antenna element and, s_{1_N} is the energy received by the 1st antenna element from the n -th neighboring antenna element.

The coupling coefficients in the diagonal $(s_{1_1}, s_{2_2}, \dots, s_{N_N})$ of the coupling matrix S represent the self-reflected energy of the antenna elements. For example, s_{1_1} is the self-reflected energy of the 1st antenna element and, s_{N_N} is the self-reflected energy of the N -th antenna element.

Accordingly, for the antenna array **14** that includes N antenna elements, a combined energy $\tilde{s}_n$ that the n -th antenna element ($n = 1, 2, \dots, N$) in the antenna array **14** receives from the neighboring antenna elements and the self-reflected energy of the n -th antenna element (for each antenna element) for each k -th frequency f_k can be calculated by:

$$\begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \\ \tilde{s}_3 \\ \vdots \\ \tilde{s}_N \end{pmatrix} = \begin{pmatrix} s_{1_1} & s_{1_2} & s_{1_3} & \cdots & s_{1_N} \\ s_{2_1} & s_{2_2} & s_{2_3} & \cdots & s_{2_N} \\ s_{3_1} & s_{3_2} & s_{3_3} & \cdots & s_{3_N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ s_{N_1} & s_{N_2} & \cdots & s_{N_N} \end{pmatrix} \cdot \begin{pmatrix} A_1 e^{j\varphi_1} \\ A_2 e^{j\varphi_2} \\ A_3 e^{j\varphi_3} \\ \vdots \\ A_N e^{j\varphi_N} \end{pmatrix}, \quad (2)$$

Accordingly, the lost energy E_{lost} can be calculated by:

$$E_{lost} = \sum_{n=1}^N |\tilde{s}|_n \quad (3)$$

Accordingly, the transmitted energy E_{trans} of the transmission system **10** can be calculated by:

$$E_{trans} = E_{total} - E_{lost} = \sum_{n=1}^N |A_n e^{j\varphi_n}| - \sum_{n=1}^N |\tilde{s}|_n \quad (4)$$

As described above, the efficiency determination unit **22** can calculate the transmission efficiency coefficient T_k using equation (1) by using the lost energy E_{lost} and the transmitted energy E_{trans} from equation (3) and (4) correspondingly.

According to an embodiment, the comparing unit **24** is configured for receiving the transmission efficiency coefficient T_k for each k -th frequency f_k from the efficiency determination unit **22**. Then, the transmission efficiency coefficient T_k is compared with the predetermined threshold value X . Further, the comparing unit **24** separates the electrical signals corresponding to the frequencies for which the transmission efficiency

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coefficient T_k is less than the predetermined threshold value X from the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient T_k is equal to or greater than the predetermined threshold value X . Then, the comparing unit **24** provides the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient T_k is equal to or greater than the predetermined threshold value X to the steering system **13**. In turn, the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient T_k is less than the predetermined threshold value X are relayed to the randomization unit **26**.

The randomization unit **26** is configured for receiving the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient T_k is less than the predetermined threshold value X and for iteratively modifying these electrical signals.

In particular, the randomization unit **26** is configured for receiving electrical signals for each frequency for which the transmission efficiency coefficient T_k is less than the predetermined threshold value X and for iteratively modifying these electrical signals by modifying their initial excitation vector V_k^{init} in each iteration.

In each iteration, the modification of each electrical signal is performed by randomizing the amplitude and phase of each electrical signal, thereby generating randomized signals. More specifically, modification of the electrical signals is performed by randomizing the amplitude and phase of each vector element in the initial excitation vector V_k^{init} of the electrical signals for each frequency at which the transmission efficiency coefficient T_k is less than a predetermined threshold value X .

According to an embodiment, the randomization is carried out by generating two random numbers α_1 and α_2 , each in the interval $[0, 1]$, and multiplying these two random numbers α_1 and α_2 by the initial amplitude A_k and initial phase φ_k correspondingly. As a result of multiplying the modified random number α_1 and α_2 by the initial amplitudes and initial phases of the electrical signals, randomized signals are obtained. Each randomized signal has a corresponding randomized phase φ_{ran} and a randomized amplitude A_{ran} . It should be noted that, for each k -th frequency, the two random numbers α_1 and α_2 can be different for each electrical signal in the n -th transmission channel ($n = 1, 2, \dots, N$).

According to an embodiment, the randomized signals for the k -th frequency f_k are represented by a randomized excitation vector V_k^{ran} :

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$$V_k^{ran} = \begin{pmatrix} A_{ran,1} e^{j\varphi_{ran,1}} \\ A_{ran,2} e^{j\varphi_{ran,2}} \\ A_{ran,3} e^{j\varphi_{ran,3}} \\ \vdots \\ A_{ran,N} e^{j\varphi_{ran,N}} \end{pmatrix}_k,$$

The randomization unit **26** is also configured for providing, in each iteration, the randomized excitation vector V_k^{ran} to the efficiency determination unit **22** for calculating an updated transmission efficiency coefficient $T_{ran,k}$ for the randomized signals. This
 5 updated transmission efficiency coefficient $T_{ran,k}$ is provided to the comparing unit **24** and compared with the predetermined threshold value X in each iteration. The randomized signals are provided by the comparing unit **24** to the steering system **13** when this transmission efficiency coefficient $T_{ran,k}$ is equal to or greater than the predetermined threshold value X .

10 In turn, when the transmission efficiency coefficient $T_{k,ran}$ for these randomized signals is less than the predetermined threshold value X , the modification system **12** performs a further iteration. The iterative modification is performed until the transmission efficiency coefficient $T_{k,ran}$ for the randomized signals is equal to or greater than the predetermined threshold value X . In other words, the electrical signals are iteratively
 15 modified by the modification system **12** until the transmission efficiency coefficient $T_{k,ran}$ is equal to or greater than the predetermined threshold value X .

As mentioned above, the randomized signals for which the transmission efficiency coefficient $T_{ran,k}$ is greater than the predetermined threshold value X are referred to herein as "optimal modified signals".

20 As mentioned above, null-points can occur at one or more frequencies within the sequence of K frequencies. The transmission efficiency coefficient T_k for the electrical signals which correspond to the frequencies at which null points may appear, is below the predetermined threshold value X . The modification system **12** receives and iteratively modifies these electrical signals until the transmission efficiency coefficient T_k for these
 25 electrical signals is equal to or greater than the predetermined threshold value X . As a result of the iterative modification of these electrical signals, the null points are removed.

According to an embodiment, the steering system **13** is configured for receiving the optimal electrical signals including the optimal modified signals and the optimal unmodified signals obtained from the modification system **12**. The steering system **13**

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processes the optimal electrical signals to generate steering electrical signals related to the optimal electrical signals. The steering electrical signals are provided to the antenna array **14** via the N transmission channels to form a steered beam for transmission in the predetermined direction.

5 Referring to **Fig. 2**, a flow chart diagram of a method **20** for transmitting radio frequency (RF) radiation in a predetermined direction at a sequence of K frequencies within a predetermined frequency band by using the transmission system **10** in **Fig. 1** is illustrated, according to an embodiment of the present invention.

Referring to **Figs. 1** and **2** together, in operation of the transmission system **10**,
 10 electrical signals for each frequency of the sequence of K frequencies $f_1, f_2, \dots, f_K$ within the predetermined frequency band are generated (block **101**). For each transmission channel, the electrical signals of the k -th frequency f_k can be represented by the expression $A_k e^{-j(2\pi \cdot f_k \cdot t + \varphi_k)}$, where A_k is the initial amplitude of this signal, φ_k is the initial phase of this signal.

15 For each k -th frequency f_k of the sequence of K frequencies $f_1, f_2, \dots, f_K$, the electrical signals can be represented by an initial excitation vector V_k^{init} having N vector elements corresponding to the N transmission channels:

$$V_k^{init} = \begin{pmatrix} A_1 e^{j\varphi_1} \\ A_2 e^{j\varphi_2} \\ A_3 e^{j\varphi_3} \\ \vdots \\ A_N e^{j\varphi_N} \end{pmatrix}_k$$

The vector elements $A_n e^{j\varphi_n}$ ($n = 1, 2, \dots, N$) relate to the corresponding electrical
 20 signals of the k -th frequency f_k . In particular, each vector element in the initial excitation vector V_k^{init} includes the initial amplitude A_n and initial phase φ_n of the corresponding electrical signals for the k -th frequency f_k .

The method further includes processing the electrical signals and calculating
 (block **102**) a transmission efficiency coefficient T_k for each k -th frequency f_k of the
 25 sequence of K frequencies $f_1, f_2, \dots, f_K$ within the predetermined frequency band.

According to an embodiment, the transmission efficiency coefficient T_k can be calculated by

$$T_k = \frac{E_{trans}}{E_{total}} \cdot 100\% \quad , \quad (5)$$

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where E_{total} is the total energy of the electrical signals for the k -th frequency f_k generated by the RF signal generator **11**, and E_{trans} is the energy transmitted by the transmission system **10** in operation for the k -th frequency f_k .

More specifically, E_{trans} can be calculated by the efficiency determination unit **22** by $E_{trans} = E_{total} - E_{lost}$, where E_{lost} is the energy that is lost by the transmission system **10** in operation for the k -th frequency f_k . In this case, E_{lost} is the energy that the transmission system **10** loses due to the mutual coupling between the antenna elements and the self-reflected energy of the antenna elements in the antenna array **14** when the transmission system **10** operates at the k -th frequency f_k .

According to an embodiment, the lost energy E_{lost} of the transmission system **10** can be determined by taking into account the mutual coupling between the antenna elements, i.e., the amount of energy that each antenna element in the antenna array **14** receives from the neighboring antenna elements and the self-reflected energy of the antenna elements, and then summing the energies for all the antenna elements.

The mutual coupling between the antenna elements and the self-reflected energy of the antenna elements in the antenna array **14** are characterized by a coupling matrix S . For an antenna array **14** that includes N antenna elements the coupling matrix S is a $N \times N$ matrix:

$$S = \begin{pmatrix} s_{11} & s_{12} & s_{13} & \cdots & s_{1N} \\ s_{21} & s_{22} & s_{23} & \cdots & s_{2N} \\ s_{31} & s_{32} & s_{33} & \cdots & s_{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ s_{N1} & s_{N2} & \cdots & s_{N3} & \cdots & s_{NN} \end{pmatrix}$$

Each non-diagonal coupling coefficient of the coupling matrix S represents the energy received by the corresponding antenna element from the neighboring antenna elements. For example, s_{12} is the energy received by the 1st antenna element from the 2nd neighboring antenna element and, s_{1N} is the energy received by the 1st antenna element from the n -th neighboring antenna element.

The coupling coefficients in the diagonal $(s_{11}, s_{22}, \dots, s_{NN})$ of the coupling matrix S represent the self-reflected energy of the antenna elements. For example, s_{11} is the self-reflected energy of the 1st antenna element and, s_{NN} is the self-reflected energy of the N -th antenna element.

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Accordingly, for an antenna array **14** that includes N antenna elements, a combined energy $\tilde{s}_n$ that the n -th antenna element ($n = 1, 2, \dots, N$) in the antenna array **14** receives from the neighboring antenna elements and the reflected energy of the n -th antenna element itself (for each antenna element) for each k -th frequency f_k can be
 5 calculated by:

$$\begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \\ \tilde{s}_3 \\ \vdots \\ \tilde{s}_N \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} & s_{13} & \cdots & s_{1N} \\ s_{21} & s_{22} & s_{23} & \cdots & s_{2N} \\ s_{31} & s_{32} & s_{33} & \cdots & s_{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ s_{N1} & s_{N2} & \cdots & s_{N3} & \cdots & s_{NN} \end{pmatrix} \cdot \begin{pmatrix} A_1 e^{j\varphi_1} \\ A_2 e^{j\varphi_2} \\ A_3 e^{j\varphi_3} \\ \vdots \\ A_N e^{j\varphi_N} \end{pmatrix}, \quad (2)$$

Accordingly, the lost energy E_{lost} can be calculated by:

$$E_{lost} = \sum_{n=1}^N |\tilde{s}|_n \quad (3),$$

where $|\tilde{s}|_n$ is the energy received by the n -th antenna element from the neighboring
 10 elements and N is the number of antenna elements in the antenna array **14**.

Accordingly, the transmitted energy E_{trans} of the transmission system **10** can be calculated as follows:

$$E_{trans} = E_{total} - E_{lost} = \sum_{n=1}^N |A_n e^{j\varphi_n}| - \sum_{n=1}^N |\tilde{s}|_n \quad (4)$$

15 As described above, the efficiency determination unit **22** can calculate the transmission efficiency coefficient T_k using equation (1) by using the lost energy E_{lost} and the transmitted energy E_{trans} from equations (3) and (4) correspondingly.

The method also includes comparing the transmission efficiency coefficient T_k (block **103**) for each k -th frequency f_k with a predetermined threshold value X . Then,
 20 electrical signals corresponding to the frequencies for which the transmission efficiency coefficient T_k is less than the predetermined threshold value X are separated from the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient T_k is equal to or greater than the predetermined threshold value X .

The method also includes providing optimal unmodified signals, which are the
 25 electrical signals (block **104**) corresponding to the frequencies for which the transmission efficiency coefficient T_k is equal to or greater than the predetermined threshold value X , to the steering system **13**. For example, the threshold value X can be in the range of 70% - 90%.

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According to an embodiment, the method also includes performing iterative modification of the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient is less than the predetermined threshold value X .

In the iterative modification, the electrical signals corresponding to the
5 frequencies for which the transmission efficiency coefficient is less than the predetermined threshold value X are modified (block **105**) by modifying the initial excitation vector V_k^{init} for these electrical signals.

According to an embodiment, in each iteration, the modification of such electrical signals is performed by randomizing the corresponding amplitudes and phases of these
10 electrical signals, thereby generating randomized signals. More specifically, the modification of the electrical signals is performed by randomizing amplitude and phase of each vector element in the initial excitation vector V_k^{init} of the electrical signals for each frequency f_k for which the transmission efficiency coefficient T_k is less than a predetermined threshold value X .

According to an embodiment, the randomization is carried out by generating two
15 random numbers α_1 and α_2 , each in the interval $[0, 1]$, and multiplying these two random numbers α_1 and α_2 by the initial amplitude A_k and initial phase φ_k correspondingly. As a result of multiplying the modified random number α_1 and α_2 by the initial amplitudes and initial phases of the electrical signals, randomized signals are obtained. Each randomized
20 signal has a corresponding randomized phase φ_{ran} and a randomized amplitude A_{ran} . It should be noted that, for each k -th frequency the two random numbers α_1 and α_2 can be different for each electrical signal in the n -th transmission channel ($n = 1, 2, \dots, N$).

According to an embodiment, the randomized signals for the k -th frequency f_k are represented by a randomized excitation vector V_k^{ran} :

$$25 \quad V_k^{ran} = \begin{pmatrix} A_{ran,1} e^{j\varphi_{ran,1}} \\ A_{ran,2} e^{j\varphi_{ran,2}} \\ A_{ran,3} e^{j\varphi_{ran,3}} \\ \vdots \\ A_{ran,N} e^{j\varphi_{ran,N}} \end{pmatrix}_k,$$

As shown in **Fig. 2**, the iterative modification also includes calculating a transmission efficiency coefficient $T_{ran,k}$ for the randomized signals, as described above, *mutatis mutandis*.

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Further, the transmission efficiency coefficient $T_{ran,k}$ for the randomized signals is compared with the predetermined threshold value X in each iteration. When this transmission efficiency coefficient T_k is equal to or greater than the predetermined threshold value X , these randomized signals, which are the optimal modified signals, are provided to the steering system **13**. In turn, when the transmission efficiency coefficient T_k for the randomized signals is less than the predetermined threshold value X , a further iteration is performed. The iterative modification is performed until the transmission efficiency coefficient $T_{ran,k}$ for the randomized signals is equal to or greater than the predetermined threshold value X . In other words, in the iterative modification, the electrical signals are modified until the transmission efficiency coefficient $T_{ran,k}$ is equal to or greater than the predetermined threshold value X .

It should be noted that null-points can occur at one or more frequencies within the sequence of K frequencies. The transmission efficiency coefficient T_k for the electrical signals which correspond to these frequencies (at which null points can occur) is below the predetermined threshold value X . These electrical signals are iteratively modified until the transmission efficiency coefficient T_k for these electrical signals is equal to or greater than the predetermined threshold value X . As a result of the iterative modification of these electrical signals, the null points are removed.

The method further includes generating the optimal electrical signals, which include the optimal modified signals and the optimal unmodified signals, and providing these optimal electrical signals to the steering system **13** to generate steering electrical signals related to the optimal electrical signals.

The method further includes providing the steering electrical signals via the N transmission channels to the antenna array **14** to form a steered beam for transmission in the predetermined direction.

Referring to **Fig. 3**, a schematic block diagram of a transmission system **30** for transmitting radio frequency (RF) radiation in a predetermined direction at a sequence of K frequencies within a predetermined frequency band is illustrated, according to another embodiment of the present invention. The transmission system **30** includes an RF generator **11**, a modification system **31** arranged downstream of the RF signal generator **11**, a steering system **13** arranged downstream of the modification system **31** and the antenna array **14** comprising a plurality of N antenna elements coupled to the steering system **13**.

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As described above, the RF generator **11** is configured and operable for generating electrical signals through N transmission channels (corresponding to N antenna elements in the antenna array **14**) for each frequency of the sequence of K frequencies $f_1, f_2, \dots, f_K$ within the predetermined frequency band.

5 The modification system **31** is configured for receiving the electrical signals from the RF generator **11**, processing these electrical signals, and obtaining optimal electrical signals having transmission efficiency coefficients greater than a predetermined threshold value X . The optimal electrical signals are relayed to the steering system **31** as described hereinbelow. The optimal electrical signals include the optimal unmodified signals
10 provided by the RF signal generator **11** and the optimal modified signals generated by the modification system **31** during operation, as described hereinbelow.

As described above, the electrical signals having the initial amplitude and initial phase, which correspond to the frequencies for which the transmission efficiency coefficient T_k is equal to or greater than the predetermined threshold X value and which
15 are provided to the steering system **13** are referred to herein as "optimal unmodified signals".

According to this embodiment, the modification system **31** includes an efficiency determination unit **22**, a comparing unit **24** arranged downstream of the efficiency determination unit **22**, and a randomization unit **26** arranged downstream of the
20 comparing unit **24**.

As can be seen in **Fig. 3**, the modification system **31** differs from the modification system (**12** in **Fig. 1**) in the fact that the randomization system **31** also includes an optimal efficiency determination system **310** arranged downstream of the randomization unit **26** and coupled to the comparing unit **24** and the efficiency determination unit **22**.

25 According to an embodiment, the optimal efficiency determination system **310** is configured for modifying the two random numbers α_1 and α_2 and for generating modified randomized signals for which the transmission efficiency coefficient $T_{mod,k}$ is greater than the transmission efficiency coefficient $T_{ran,k}$ of the randomized signals. The generating of the modified randomized signals is carried out by using two modified random numbers.
30 These modified randomized signals are obtained by the optimal efficiency determination system **310** by performing a predetermined number P of sub-iterations as described below in detail.

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According to an embodiment, the efficiency determination unit **22** is configured to receive the electrical signals for each k -th frequency f_k of the sequence of K frequencies $f_1, f_2, \dots, f_K$, to process these electrical signals and to calculate for each k -th frequency f_k the transmission efficiency coefficient T_k of the transmission system **30** as described
 5 above, *mutatis mutandis*.

According to an embodiment, the comparing unit **24** is configured for receiving the transmission efficiency coefficient T_k for each k -th frequency f_k from the efficiency determination unit **22**. Then, the transmission efficiency coefficient T_k is compared with the predetermined threshold value X . Further, the comparing unit **24** separates the
 10 electrical signals corresponding to the frequencies for which the transmission efficiency coefficient T_k is less than the predetermined threshold value X from the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient T_k is equal to or greater than the predetermined threshold value X . Then, the comparing unit **24** provides the electrical signals corresponding to the frequencies for which the
 15 transmission efficiency coefficient T_k is equal to or greater than the predetermined threshold value X to the steering system **13**. In turn, the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient T_k is less than the predetermined threshold value X are relayed to the randomization unit **26**. The randomization unit **26** is configured for receiving the electrical signals corresponding to
 20 the frequencies for which the transmission efficiency coefficient T_k is less than the predetermined threshold value X from the comparing unit **24**. The randomization unit **26** is also configured for iteratively modifying the electrical signals, thereby generating randomized signals.

As described above, with reference to **Fig. 1**, the randomization unit **26** is
 25 configured for receiving electrical signals for the frequencies for which the transmission efficiency coefficient T_k is less than the predetermined threshold value X , and for iteratively modifying these electrical signals by modifying their initial excitation vector V_k^{init} . In each iteration, the modification of each electrical signal is performed by randomizing the amplitude and phase of each electrical signal, thereby generating the
 30 randomized signals. More specifically, the modification of the electrical signals is performed by randomizing amplitude and phase of each vector element in the initial excitation vector V_k^{init} of the electrical signals for each frequency at which the transmission efficiency coefficient T_k is less than a predetermined threshold value X .

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According to an embodiment, the randomization of the amplitude and phase of each vector element in the initial excitation vector V_k^{init} is carried out by generating two random numbers α_1 and α_2 , each in the interval $[0, 1]$, and multiplying these two random numbers α_1 and α_2 by the initial amplitude A_k and initial phase φ_k correspondingly. As a result of multiplying the modified random number α_1 and α_2 by the initial amplitudes and initial phases of the electrical signals, randomized signals are obtained. Each randomized signal has a corresponding randomized phase φ_{ran} and a randomized amplitude A_{ran} . It should be noted that for each k -th frequency, the two random numbers α_1 and α_2 can be different for each electrical signal in the n -th transmission channel ($n = 1, 2, \dots, N$).

According to an embodiment, the randomized signals for the k -th frequency f_k are represented by a randomized excitation vector V_k^{ran} :

$$V_k^{ran} = \begin{pmatrix} A_{ran,1} e^{j\varphi_{ran,1}} \\ A_{ran,2} e^{j\varphi_{ran,2}} \\ A_{ran,3} e^{j\varphi_{ran,3}} \\ \vdots \\ A_{ran,N} e^{j\varphi_{ran,N}} \end{pmatrix}_k,$$

The randomization unit **26** is also configured for providing, in each iteration, the randomized excitation vectors to the efficiency determination unit **22** for calculating an updated transmission efficiency coefficient $T_{ran,k}$.

According to this embodiment, this updated transmission efficiency coefficient $T_{ran,k}$ is relayed by the efficiency determination unit **22** to the optimal efficiency determination system **310** in each iteration of the modification system **31**.

According to an embodiment, the optimal efficiency determination system **310** is configured for receiving in each iteration of the modification system **31** the electrical signals for which the transmission efficiency coefficient T_k is less than the predetermined threshold value X from the comparing unit **24**. The optimal efficiency determination system **310** also receives the two random numbers α_1 and α_2 for each transmission channel from the randomization unit **26** and the corresponding updated transmission efficiency coefficient $T_{ran,k}$ for the randomized signals from the efficiency determination unit **22**.

According to an embodiment, the optimal efficiency determination system **310** includes a modification unit **311**, an efficiency determination sub-unit **312** arranged downstream of the modification unit **311**, a comparing sub-unit **314** arranged downstream

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of the efficiency determination sub-unit **312**, and a storing unit **313** coupled to the comparing sub-unit **314**.

According to an embodiment, the modification unit **311** is configured, in each sub-iteration p (where p is sub-iteration number $p = 1, 2, \dots, P$), for receiving the electrical signals for which the transmission efficiency coefficient T_k is less than the predetermined threshold value X from the comparing unit **24** and the corresponding two random numbers α_1 and α_2 for each electrical signal from the randomization unit **26**, and for modifying these electrical signals, thereby generating modified randomized signals.

According to an embodiment, the modification of these electrical signals is carried out by modifying the initial amplitudes and initial phases of these electrical signals. More specifically, the modification of these electrical signals is performed by modifying the initial amplitude and initial phase of each vector element in the initial excitation vector V_k^{init} of these electrical signals.

According to an embodiment, the modification of the amplitudes and phases of the electrical signals is carried out by multiplying the initial amplitude and initial phase of each electrical signal by the corresponding two modified random numbers α_{1mod} and α_{2mod} .

According to an embodiment, the two modified random numbers α_{1mod} and α_{2mod} are the numbers in the proximity of the two random numbers α_1 and α_2 . The two modified random numbers α_{1mod} and α_{2mod} are generated by sub-iteratively modifying the values of the two random numbers α_1 and α_2 (i.e., modifying the two random numbers α_1 and α_2 in each sub-iteration p).

According to an embodiment, modification of the two random numbers α_1 and α_2 is carried out by sub-iteratively adding $\pm \Delta\beta_1 \cdot p$ and $\pm \Delta\beta_2 \cdot p$ ($p = 1, 2, \dots, P$) to the two random numbers α_1 and α_2 , correspondingly. The proximity increments $\Delta\beta_1$ and $\Delta\beta_2$ can, for example, be in the range of 0.01- 0.001. Accordingly, in each sub-iteration p , $\alpha_{1mod,p} = \alpha_1 \pm \Delta\beta_1 \cdot p$ and $\alpha_{2mod,p} = \alpha_2 \pm \Delta\beta_2 \cdot p$. The number of sub-iterations P can, for example, be in the range of 500-1000.

For example, when in the first sub-iteration ($p = 1$) $\Delta\beta_1 = 0.001$ and $\Delta\beta_2 = 0.003$, the two modified random numbers can be $\alpha_{1mod,1} = \alpha_1 + 0.001 \cdot 1$ and $\alpha_{2mod,1} = \alpha_2 + 0.003 \cdot 1$. Accordingly, in the second sub-iteration ($p = 2$) $\alpha_{1mod,2} = \alpha_1 + 0.001 \cdot 2$ and $\alpha_{2mod,2} = \alpha_2 + 0.003 \cdot 2$.

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As a result of multiplying the two modified random numbers α_{1mod} and α_{2mod} by the initial amplitudes and initial phases of the electrical signals, modified randomized signals are obtained. As a result of the modification sub-iterative procedure, for each transmission channel n (where $n = 1, 2, \dots, N$), each modified randomized signal has a
 5 corresponding modified randomized phase $(\varphi_{mod})_p$ and a modified randomized amplitude $(A_{mod})_p$.

According to an embodiment, in each sub-iteration p , the modified randomized signals for the k -th frequency f_k are represented by a modified excitation vector V_k^{mod} :

$$V_k^{mod} = \begin{pmatrix} A_{mod,1} e^{j\varphi_{mod,1}} \\ A_{mod,2} e^{j\varphi_{mod,2}} \\ A_{mod,3} e^{j\varphi_{mod,3}} \\ \vdots \\ A_{mod,N} e^{j\varphi_{mod,N}} \end{pmatrix}_k ,$$

10 The modification unit **311** is also configured for relaying these modified randomized signals to the sub efficiency determination unit **312** in each sub-iteration p .

According to an embodiment, in each sub-iteration p , the efficiency determination sub-unit **312** is configured for receiving the modified randomized signals from the modification unit **311**, and for calculating the transmission efficiency coefficient $T_{mod,k}$
 15 for these modified randomized signals as described above, *mutatis mutandis*.

Thus, in each sub-iteration of the optimal efficiency determination system **310** the electrical signals are modified and transmission efficiency coefficient $T_{mod,k}$ is calculated for the modified randomized signals, as described above.

According to an embodiment, the storing unit **313** is configured for storing the
 20 transmission efficiency coefficient $T_{mod,k}$ and the corresponding excitation vector V_k^{mod} of the modified randomized signals received from the efficiency determination sub-unit **312**, and the transmission efficiency coefficient $T_{ran,k}$ of the randomized signals, and the corresponding randomized vector V_k^{ran} obtained from the efficiency determination unit **22**.

25 The transmission efficiency coefficient $T_{ran,k}$ (or $T_{mod,k}$) stored in the storing unit **313** is referred to herein as "stored efficiency coefficient", and the corresponding excitation vector V_k^{ran} (or V_k^{mod}) is referred to herein as "stored excitation vector".

In operation, for each sub-iteration p , the comparing sub-unit **314** is configured for receiving the stored coefficient from the storing unit **313** and the transmission

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efficiency coefficient $T_{mod,k}$ of the modified randomized signals from the efficiency determination sub-unit **312**. The comparing sub-unit **314** is also configured for comparing the value of the stored efficiency coefficient with the current value of the transmission efficiency coefficient $T_{mod,k}$ of the modified randomized signals. The comparing sub-unit
 5 **314** is also configured for providing the transmission efficiency coefficient $T_{mod,k}$ of the modified randomized signals and the corresponding excitation vector V_k^{mod} to the storing unit **313** for storing thereof when in a certain sub-iteration p the value of this transmission efficiency coefficient $T_{mod,k}$ is greater than the value of stored efficiency coefficient.

More specifically, the stored efficiency coefficient and the stored excitation vector
 10 in the storing unit **313** are replaced with the transmission efficiency coefficient $T_{mod,k}$ and the corresponding excitation vector V_k^{mod} when the value of this transmission efficiency coefficient $T_{mod,k}$ is greater than the value of the stored efficiency coefficient. Alternatively, when the value of this transmission efficiency coefficient $T_{mod,k}$ is equal to or less than the value of the stored efficiency coefficient, the stored efficiency coefficient
 15 remains unchanged.

It should be understood that in the first sub-iteration ($p = 1$), the storing unit **313** receives the transmission efficiency coefficient $T_{ran,k}$ of the randomized signals and the corresponding excitation vector V_k^{ran} for storing. In other words, the stored efficiency coefficient in the first sub-iteration is the transmission efficiency coefficient $T_{ran,k}$ of the
 20 randomized signals and the stored excitation vector is the corresponding excitation vector V_k^{ran} .

Accordingly, in the first sub-iteration, the comparing sub-unit **314** compares the value of the transmission efficiency coefficient $T_{ran,k}$ of the randomized signals with the value of the transmission efficiency coefficient $T_{mod,k}$ of the modified randomized signals.

25 This process is performed in each sub-iteration p of the optimal efficiency determination system **310**. After completing the predetermined number P of sub-iterations, the storing unit **313** stores the highest value of the transmission efficiency coefficient $T_{ran,k}$ (or $T_{mod,k}$) from all the sub-iterations P and the excitation vector V_k^{mod} (or V_k^{ran}) corresponding to this highest value of the transmission efficiency coefficient.

30 The stored efficiency coefficient, which is stored in the storing unit **313** after completing the predetermined number P of sub-iterations, is referred to herein as "highest

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transmission efficiency coefficient T_h ", while the corresponding excitation vector is referred to herein as "optimal excitation vector V_k^h ".

After completing the predetermined number P of sub-iterations, the storing unit **313** is also configured for providing the highest transmission efficiency coefficient T_h to the comparing unit **24** for comparing this highest transmission efficiency coefficient T_h with the predetermined threshold value X . The optimal excitation vector V_k^h , for which the highest transmission efficiency coefficient T_h is equal to or greater than the predetermined threshold value X , represents the optimal modified signals.

The comparing unit **24** is also configured for relaying optimal electrical signals including the optimal modified signals and the optimal unmodified signals to the steering system **13**.

In turn, when the highest transmission efficiency coefficient T_h is less than the predetermined threshold value X , the modification system **31** continues its operation and performs a further iteration.

According to an embodiment, the steering system **13** is configured for receiving the optimal electrical signals obtained from the modification system **31**, and for generating steering electrical signals related to the optimal electrical signals.

The steering electrical signals are provided to the antenna array **14** via the N transmission channels to form a steered beam for transmission in the predetermined direction.

Referring to **Fig. 4**, a flow chart diagram of a method **40** for transmitting radio frequency (RF) radiation in a predetermined direction at a sequence of K frequencies within a predetermined frequency band by using the transmission system **30** in **Fig. 3** is illustrated, according to an embodiment of the present invention. The method **40** of operation of the transmission system **30** differs from the method (20 in **Fig. 2**) of operation of the transmission system **10** in the fact that it further includes a step of obtaining, by the optimal efficiency determination system **310**, modified randomized signals for which the transmission efficiency coefficient $T_{mod,k}$ is greater than the transmission efficiency coefficient $T_{ran,k}$ of the randomized signals.

Referring to **Fig. 5**, a flow chart diagram of a method **50** for providing the modified randomized signals for which the transmission efficiency coefficient $T_{mod,k}$ is greater than the transmission efficiency coefficient $T_{ran,k}$ of the randomized signals by the

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optimal efficiency determination system **310** in **Fig. 3** is illustrated, according to an embodiment of the present invention.

According to this embodiment, the method **50** includes receiving and storing (block **51**) the transmission efficiency coefficient $T_{ran,k}$ of the randomized signals and the corresponding randomized vector V_k^{ran} . The method further includes sub-iteratively modifying (block **52**) the electrical signals for which the transmission efficiency coefficient is less than the predetermined threshold value X obtained from the RF generator **11**. The modification of these electrical signals is carried out by modifying the initial amplitudes and initial phases of these electrical signals in each sub-iteration.

More specifically, the modification of these electrical signals is performed by modifying amplitude and phase of each vector element in the initial excitation vector V_k^{init} of these electrical signals in each sub-iteration. The modification of the amplitudes and phases of the electrical signals is carried out by multiplying the initial amplitude and initial phase of each electrical signal by the corresponding two modified random numbers α_{1mod} and α_{2mod} . The two modified random numbers α_{1mod} and α_{2mod} are the numbers in the proximity of the two random numbers α_1 and α_2 .

According to an embodiment, the two modified random numbers α_{1mod} and α_{2mod} are generated by sub-iteratively modifying the values of the two random numbers α_1 and α_2 (i.e., modifying the random numbers α_1 and α_2 in each sub-iteration).

According to an embodiment, the modification of the two random numbers α_1 and α_2 is carried out by sub-iteratively adding $\pm \Delta\beta_1 \cdot p$ and $\pm \Delta\beta_2 \cdot p$ to the two random numbers α_1 and α_2 , correspondingly, where $p = 1, 2, \dots, P$, where P is the total number of sub-iterations. The proximity increments $\Delta\beta_1$ and $\Delta\beta_2$ can, for example, be in the range of 0.01- 0.001. Accordingly, in each sub-iteration p , $\alpha_{1mod,p} = \alpha_1 \pm \Delta\beta_1 \cdot p$ and $\alpha_{2mod,p} = \alpha_2 \pm \Delta\beta_2 \cdot p$. The number of the sub-iterations P can, for example, be in the range of 500-1000.

For example, when in the first sub-iteration ($p = 1$) $\Delta\beta_1 = 0.001$ and $\Delta\beta_2 = 0.003$, the modified two random numbers can be $\alpha_{1mod,1} = \alpha_1 + 0.001 \cdot 1$ and $\alpha_{2mod,1} = \alpha_2 + 0.003 \cdot 1$. Accordingly, in the second sub-iteration ($p = 2$) $\alpha_{1mod,2} = \alpha_1 + 0.001 \cdot 2$ and $\alpha_{2mod,2} = \alpha_2 + 0.003 \cdot 2$.

As a result of multiplying the two modified random numbers α_{1mod} and α_{2mod} by the initial amplitudes and initial phases of the electrical signals, modified randomized signals are obtained. As a result of the modification sub-iterative procedure, in each sub iteration p , for each transmission channel n ($n = 1, 2, \dots, N$), each modified randomized

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signal has a corresponding modified randomized phase $(\varphi_{mod})_p$ and a modified randomized amplitude $(A_{mod})_p$. The modified randomized signals for the k -th frequency f_k can be represented by a modified excitation vector V_k^{mod} :

$$V_k^{mod} = \begin{pmatrix} A_{mod,1} e^{j\varphi_{mod,1}} \\ A_{mod,2} e^{j\varphi_{mod,2}} \\ A_{mod,3} e^{j\varphi_{mod,3}} \\ \vdots \\ A_{mod,N} e^{j\varphi_{mod,N}} \end{pmatrix}_k$$

5 As shown in **Fig. 5**, the method also includes calculating (block **53**) the transmission efficiency coefficient $T_{mod,k}$ for these modified randomized signals in each sub-iteration. The transmission efficiency coefficient $T_{mod,k}$ is calculated by using equations (1), (3) and (4), *mutatis mutandis*.

As also shown in **Fig. 5**, the method also includes comparing (block **54**) the
10 transmission efficiency coefficient $T_{mod,k}$ for the modified randomized signals obtained in the previous step (block **53**) with the previously stored transmission efficiency coefficient in each sub-iteration and replacing (block **55**) the previously stored transmission efficiency coefficient with the transmission efficiency coefficient $T_{mod,k}$ for the modified randomized signals when this transmission efficiency coefficient $T_{mod,k}$ is greater than the
15 previously stored transmission efficiency coefficient.

In turn, when this transmission efficiency coefficient $T_{mod,k}$ is less than the previously stored transmission efficiency coefficient, the previously stored transmission efficiency coefficient remains unchanged (block **56**).

The stored efficiency coefficient obtained after completing the predetermined
20 number P of the sub-iterations is referred to herein as "highest transmission efficiency coefficient T_h " and the corresponding excitation vector is referred to herein as "optimal excitation vector V_k^h ". It should be understood that optimal transmission efficiency coefficient T_h is the maximal transmission efficiency coefficient obtained during the P sub-iterations. The optimal excitation vector V_k^h , represents the modified randomized
25 signals for which the transmission efficiency coefficient $T_{mod,k}$ is greater than the transmission efficiency coefficient $T_{ran,k}$ of the randomized signals.

Turning back to **Fig. 4**, after completing the predetermined number P of sub-iterations in the method **50** described above, the method **40** further includes comparing the highest transmission efficiency coefficient T_h obtained in the method **50** with the

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predetermined threshold value X in each iteration of the modification system **31**. Modified randomized signals for which the highest transmission efficiency coefficient T_h is greater than the predetermined threshold value X are the optimal modified signals.

According to an embodiment, the method **40** of operation of the transmission
5 system **30** also includes relaying (block **105**) the optimal electrical signals including the modified randomized signals from the optimal efficiency determination system **310** (in **Fig. 3**) and the optimal unmodified signals obtained from the RF signal generator **11** for which the transmission efficiency coefficients are equal to or greater than the predetermined threshold value X to the steering system **13**.

10 In turn, when optimal transmission efficiency coefficient T_{opt} for the optimal electrical signals is less than the predetermined threshold value X , a further iteration is performed by the modification system **31**. The iterative modification is performed by the modification system **31** until the optimal transmission efficiency coefficient T_{opt} for the modified randomized signals is equal to or greater than the predetermined threshold value
15 X .

Referring to **Fig. 6**, examples of the frequency dependence (curve **61**) of the transmitted energy of the transmission system **30** shown in **Fig. 3** and the frequency dependence (curve **62**) of the transmitted energy of a conventional system, which does not include the modification system **31**, are illustrated. As mentioned above, null points
20 occur at the frequencies at which the amount of the transmitted energy is less than a certain predetermined threshold value. For example, this threshold value can be in the range of 70%-90%.

As can be seen in **Fig. 6**, several null points appear on a curve **62** at the frequencies below 2.5 GHz. For example, a point **63** at frequency 2.1 GHz is a null point, since the
25 transmitted energy corresponding to this point is less than 40%. As can also be seen, adding the modification system **31** to a conventional system, can modify the transmitted energy characteristics. In particular, the transmitted energy is enhanced at the null points, which occur at the frequency range below 2.5 GHz. For example, at a point **64** on a curve **61** (which corresponds to the same frequency 2.1 GHz as the point **63** on curve **62**) the
30 transmitted energy is greater than 70%.

Thus, the implementation of the modification system **31** in a conventional system significantly extends the operation frequency band of the conventional system.

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Fig. 7A illustrates a radiation azimuth pattern **71** generated by the transmission system **30** shown in **Fig. 3** at the frequency of 2.0269 GHz, and a radiation azimuth pattern **72** generated by a conventional system which does not include the modification system **31** at that same frequency.

5 As can be seen, the adding of the modification system **31** to the conventional system improves transmission characteristics in terms of both the gain and the directivity of transmission.

The improved transmission characteristics can also be observed in a broad frequency range. For example, **Fig. 7B** illustrates a radiation azimuth pattern **73** generated
10 by the transmission system **30** shown in **Fig. 3** at the frequency of 1.6725 GHz, and a radiation azimuth pattern **74** generated by a conventional system which does not include the modification system **31** at that same frequency.

As such, those skilled in the art to which the present invention pertains, can appreciate that while the present invention has been described in terms of preferred
15 embodiments, the concept upon which this disclosure is based may readily be utilized as a basis for the designing of other structures, systems and processes for carrying out the several purposes of the present invention.

Also, it is to be understood that the phraseology and terminology employed herein are for the purpose of description and should not be regarded as limiting.

20 Finally, it should be noted that the word “comprising” as used throughout the appended claims is to be interpreted to mean “including but not limited to”.

It is important, therefore, that the scope of the invention is not construed as being limited by the illustrative embodiments set forth herein. Other variations are possible within the scope of the present invention as defined in the appended claims. Other combinations
25 and sub-combinations of features, functions, elements and/or properties may be claimed through amendment of the present claims or presentation of new claims in this or a related application. Such amended or new claims, whether they are directed to different combinations or directed to the same combinations, whether different, broader, narrower or equal in scope to the original claims, are also regarded as included within the subject matter
30 of the present description.

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CLAIMS:

1. A transmission system (10) for transmitting radio frequency (RF) radiation in a predetermined direction at a sequence of K frequencies by an antenna array (14) comprising a predetermined number N of antenna elements, comprising:
- 5 an RF signal generator (11) configured for generating electrical signals having an initial amplitude and an initial phase through N transmission channels corresponding to N antenna elements, at the sequence of K frequencies;
- a modification system (12) arranged downstream of the RF signal generator (11), configured for receiving and processing the electrical signals from said RF signal generator (11) for obtaining optimal electrical signals for which a transmission efficiency coefficient of the transmission system is equal to or greater than a predetermined threshold value, the optimal electrical signals including optimal unmodified signals provided by the RF signal generator (11) and optimal modified signals generated by the modification system (12); and
- 10 a steering system (13) arranged downstream of said modification system (12) and coupled to said antenna array (14), and configured for (i) receiving the optimal electrical signals obtained from the modification system (12), (ii) generating steering electrical signals related to the optimal electrical signals and (iii) relaying the steering electrical signals via the N transmission channels to the antenna array (14) to form a steered beam
- 20 for transmission in the predetermined direction.
2. The transmission system of claim 1, wherein the modification system (12) comprises:
- an efficiency determination unit (22) configured for receiving the electrical signals at the sequence of K frequencies from the RF signal generator (11) and for
- 25 calculating the transmission efficiency coefficient of the transmission system for each k -th frequency f_k ;
- a comparing unit (24) configured for
- receiving the transmission efficiency coefficient for each k -th frequency f_k from the efficiency determination unit (22),
- 30 comparing the transmission efficiency coefficient with the predetermined threshold value,
- separating electrical signals corresponding to the frequencies for which the transmission efficiency coefficient is less than the predetermined threshold

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value from the electrical corresponding to the frequencies for which the transmission efficiency coefficient is equal to or greater than the predetermined threshold value, and

5 providing the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient is equal to or greater than the predetermined threshold value to the steering system (13); and a randomization unit (26) configured for

10 receiving the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient is less than a predetermined threshold value,

iteratively modifying these electrical signals by randomizing amplitude and phase of these electrical signals, thereby generating randomized signals, each randomized signal having a corresponding randomized amplitude and randomized phase, and

15 providing in each iteration said randomized signals to the efficiency determination unit (22) to calculate transmission efficiency coefficient for said randomized signals.

3. The transmission system of claim 1, wherein the optimal modified signals are the randomized signals for which the transmission efficiency coefficient is equal to or greater
20 than the predetermined threshold value and the optimal unmodified signals are electrical signals having said initial amplitude and said initial phase for which the transmission efficiency coefficient is equal to or greater than the predetermined threshold value.

4. The transmission system of any one of claims 1 to 3, wherein the randomization system (12) is configured for performing iterative modification of the electrical signals
25 corresponding to the frequencies for which the transmission efficiency coefficient is less than the predetermined threshold value until the transmission efficiency coefficient for these electrical signals is equal to or greater than said predetermined threshold value.

5. The transmission system of any one of claims 1 to 4, wherein the transmission efficiency coefficient is calculated by:

30
$$T_k = \frac{E_{trans}}{E_{total}} \cdot 100\% ,$$

where E_{total} is the total energy of the electrical signals for the k -th frequency f_k generated by the RF signal generator and E_{trans} is the energy transmitted in operation for the k -th

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frequency f_k and where E_{trans} is calculated by the efficiency determination unit (22) by $E_{trans} = E_{total} - E_{lost}$, where E_{lost} is the energy that is lost by the transmission system in operation for the k -th frequency f_k .

6. The transmission system of claim 5, wherein the lost energy E_{lost} is calculated by:

$$E_{lost} = \sum_{n=1}^N |\tilde{s}|_n, \quad (5)$$

where $\tilde{s}_n$ is a combined energy that an n -th antenna element ($n = 1, 2, \dots, N$) in the antenna array (14) receives from neighboring antenna elements and a self-reflected energy of the n -th antenna element.

7. The transmission system of claim 6, wherein said combined energy $\tilde{s}_n$ is calculated by:

$$\begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \\ \tilde{s}_3 \\ \vdots \\ \tilde{s}_N \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} & s_{13} & \cdots & s_{1N} \\ s_{21} & s_{22} & s_{23} & \cdots & s_{2N} \\ s_{31} & s_{32} & s_{33} & \cdots & s_{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ s_{N1} & s_{N2} & \cdots & s_{N3} & \cdots & s_{NN} \end{pmatrix} \cdot \begin{pmatrix} A_1 e^{j\varphi_1} \\ A_2 e^{j\varphi_2} \\ A_3 e^{j\varphi_3} \\ \vdots \\ A_N e^{j\varphi_N} \end{pmatrix},$$

where $V_k^{init} = \begin{pmatrix} A_1 e^{j\varphi_1} \\ A_2 e^{j\varphi_2} \\ A_3 e^{j\varphi_3} \\ \vdots \\ A_N e^{j\varphi_N} \end{pmatrix}_k$ is an initial excitation vector representing the electrical

signals for N transmission channels for each k -th frequency f_k , and

$$S = \begin{pmatrix} s_{11} & s_{12} & s_{13} & \cdots & s_{1N} \\ s_{21} & s_{22} & s_{23} & \cdots & s_{2N} \\ s_{31} & s_{32} & s_{33} & \cdots & s_{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ s_{N1} & s_{N2} & \cdots & s_{N3} & \cdots & s_{NN} \end{pmatrix} \text{ is a coupling matrix characterizing mutual coupling}$$

15 between antenna elements and a self-reflected energy of the antenna elements in the antenna array (14).

8. The transmission system of claim 7, wherein the transmitted energy E_{trans} of the transmission system is calculated by:

$$E_{trans} = E_{total} - E_{lost} = \sum_{n=1}^N |A_n e^{j\varphi_n}| - \sum_{n=1}^N |\tilde{s}|_n$$

20 9. The transmission system of claim 2, wherein randomizing the amplitude and the phase of the electrical signals is carried out by iteratively generating two random

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numbers, each in the interval $[0, 1]$, and multiplying the initial amplitude and the initial phase of said electrical signals by the two random numbers, correspondingly; thereby generating said randomized signals.

10 **10.** The transmission system of claim 9, wherein said two random numbers are different for each electrical signal in an n -th transmission channel ($n = 1, 2, \dots, N$).

11. The transmission system of any one of claims 1 to 10, wherein the randomization system (12) further includes an optimal efficiency determination system (310) arranged downstream of the randomization unit (26) and coupled to the comparing unit (24) and to the efficiency determination unit (22), said optimal efficiency determination system (310)
10 is configured for sub-iteratively modifying said two random numbers thereby, generating in each sub-iteration two modified random numbers, and generating modified randomized signals for which the transmission efficiency coefficient is greater than the transmission efficiency coefficient of the randomized signals by using said two modified random numbers.

15 **12.** The transmission system of claim 11, wherein the optimal efficiency determination system (310) is configured to perform a predetermined number P of sub-iterations to generate said modified randomized signals for which the transmission efficiency coefficient is greater than the transmission efficiency coefficient of the randomized signals provided by the randomization unit (26).

20 **13.** The transmission system of claims 11 or 12, wherein the optimal efficiency determination system (310) comprises:

a modification unit (311) configured for (i) receiving the electrical signals for which the transmission efficiency coefficient is less than the predetermined threshold value from the comparing unit (24) and (ii) receiving the corresponding two random
25 numbers for each electrical signal from the randomization unit (26) and (iii) sub-iteratively modifying said electrical signals, thereby generating said modified randomized signals;

an efficiency determination sub-unit (312) arranged downstream of the modification unit (311) configured for sub-iteratively receiving the modified randomized
30 signals from the modification unit (311) and calculating a transmission efficiency coefficient for these modified randomized signals;

a storing unit (314) configured for storing the transmission efficiency coefficient for the modified randomized signals and a corresponding excitation vector sub-iteratively

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received from the efficiency determination sub-unit (312), and storing the transmission efficiency coefficient for the randomized signals, and a corresponding randomized vector iteratively obtained from the efficiency determination unit; and

a comparing sub-unit (313) coupled to the storing unit (314) configured for
 5 sub-iteratively receiving a stored efficiency coefficient from the storing unit (314) and the transmission efficiency coefficient for the modified randomized signals from the efficiency determination sub-unit (312),

sub-iteratively comparing the stored efficiency coefficient with the transmission efficiency coefficient of the modified randomized signals, and

10 providing the transmission efficiency coefficient for the modified randomized signals and the corresponding excitation vector to the storing unit (314) for storing thereof when the value of this transmission efficiency coefficient for the modified randomized signals is greater than the value of said stored efficiency coefficient.

14. The transmission system of claim 13, wherein the modification of the electrical
 15 signals corresponding to the frequencies for which the transmission efficiency coefficient is less than the predetermined threshold value by the modification unit (311) is carried out by multiplying the initial amplitude and initial phase of each electrical signal by corresponding two modified random numbers.

15. The transmission system of any one of claims claim 11 to 14, wherein said two
 20 modified random numbers are generated by sub-iteratively adding $\pm A\beta_1 \cdot p$ and $\pm A\beta_2 \cdot p$ to the two random numbers, correspondingly, where $p = 1, 2, \dots, P$.

16. A method for transmitting radio frequency (RF) radiation in a predetermined direction at a sequence of K frequencies by an antenna array (14) comprising a predetermined number N of antenna elements, comprising:

25 generating electrical signals having an initial amplitude and an initial phase at a sequence of K frequencies;

processing the electrical signals and obtaining optimal electrical signals for which the transmission efficiency coefficient is equal to or greater than a predetermined threshold value, the optimal electrical signals including optimal unmodified signals and
 30 optimal modified signals;

generating steering electrical signals related to the optimal electrical signals; and

forming a steered beam based on the steering electrical signals for transmission in the predetermined direction.

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17. The method of claim 16, wherein the obtaining of the optimal electrical signals comprises:

calculating a transmission efficiency coefficient for each k -th frequency f_k of the sequence of K frequencies;

5 comparing the transmission efficiency coefficient for each k -th frequency f_k with a predetermined threshold value;

separating electrical signals corresponding to the frequencies for which the transmission efficiency coefficient is less than the predetermined threshold value from the electrical corresponding to the frequencies for which the transmission efficiency
10 coefficient is equal to or greater than the predetermined threshold value;

iteratively modifying the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient is less than a predetermined threshold value by randomizing amplitude and phase of these electrical signals, thereby generating randomized signals; and

15 providing optimal electrical signals including optimal unmodified signals and optimal modified signals.

18. The method of claims 16 or 17, wherein the optimal modified signals are the randomized signals for which the transmission efficiency coefficient is equal to or greater than the predetermined threshold value, and the optimal unmodified signals are the
20 electrical signals having said initial amplitude and said initial phase for which the transmission efficiency coefficient is equal to or greater than the predetermined threshold value.

19. The method of claim 17, wherein the iterative modifying of the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient is less
25 than the predetermined threshold value, is performed until the transmission efficiency coefficient for these electrical signals is equal to or greater than said predetermined threshold value thereby generating the optimal modified signals.

20. The method of claim 17, wherein the transmission efficiency coefficient is calculated by:

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$$T_k = \frac{E_{trans}}{E_{total}} \cdot 100\% \quad ,$$

where E_{total} is the total energy of the electrical signals for the k -th frequency f_k , E_{trans} is the energy transmitted in operation for the k -th frequency f_k and where E_{trans} is calculated

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by $E_{trans} = E_{total} - E_{lost}$, where E_{lost} is the energy that is lost in operation for the k -th frequency f_k .

21. The transmission system of any one of claims 16 to 20, wherein the lost energy E_{lost} is calculated by:

$$E_{lost} = \sum_{n=1}^N |\tilde{s}|_n$$

where $\tilde{s}_n$ is a combined energy that an n -th antenna element in the antenna array (14) receives from neighboring antenna elements and a self-reflected energy of the n -th antenna element.

22. The method of claim 21, wherein said combined energy $\tilde{s}_n$ is calculated by:

$$\begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \\ \tilde{s}_3 \\ \vdots \\ \tilde{s}_N \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} & s_{13} & \cdots & s_{1N} \\ s_{21} & s_{22} & s_{23} & \cdots & s_{2N} \\ s_{31} & s_{32} & s_{33} & \cdots & s_{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ s_{N1} & s_{N2} & \cdots & s_{N3} & \cdots & s_{NN} \end{pmatrix} \cdot \begin{pmatrix} A_1 e^{j\varphi_1} \\ A_2 e^{j\varphi_2} \\ A_3 e^{j\varphi_3} \\ \vdots \\ A_N e^{j\varphi_N} \end{pmatrix},$$

where $V_k^{init} = \begin{pmatrix} A_1 e^{j\varphi_1} \\ A_2 e^{j\varphi_2} \\ A_3 e^{j\varphi_3} \\ \vdots \\ A_N e^{j\varphi_N} \end{pmatrix}_k$ is an initial excitation vector representing the electrical

signals for N transmission channels for each k -th frequency f_k and

$S = \begin{pmatrix} s_{11} & s_{12} & s_{13} & \cdots & s_{1N} \\ s_{21} & s_{22} & s_{23} & \cdots & s_{2N} \\ s_{31} & s_{32} & s_{33} & \cdots & s_{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ s_{N1} & s_{N2} & \cdots & s_{N3} & \cdots & s_{NN} \end{pmatrix}$ is a coupling matrix characterizing mutual coupling

between antenna elements and the self-reflected energy of the antenna elements in the

antenna array (14).

23. The method of claim 22, wherein the transmitted energy E_{trans} of the transmission system is calculated by:

$$E_{trans} = E_{total} - E_{lost} = \sum_{n=1}^N |A_n e^{j\varphi_n}| - \sum_{n=1}^N |\tilde{s}|_n$$

24. The method of claim 23, wherein randomizing the amplitude and the phase of the electrical signals is carried out by generating two random numbers, each in the interval

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[0, 1], and multiplying the initial amplitude and the initial phase of said electrical signals by the two random numbers, correspondingly.

25. The method of claim 24, wherein said two random numbers can be different for each electrical signal in an n -th transmission channel selected from the N transmission channels.

26. The method of claims 16 to 25, wherein the iteratively modifying of the electrical signals further includes providing modified randomized signals for which the transmission efficiency coefficient is greater than the transmission efficiency coefficient of the randomized signals.

27. The method of claim 26, wherein the providing of the modified randomized signals for which the transmission efficiency coefficient is greater than the transmission efficiency coefficient of the randomized signals comprises:

receiving and storing the transmission efficiency coefficient of the randomized signals and a corresponding randomized excitation vector;

sub-iteratively modifying the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient is less than the predetermined threshold value, thereby generating the modified randomized signals;

sub-iteratively calculating a transmission efficiency coefficient for these modified randomized signals;

sub-iteratively comparing the transmission efficiency coefficient for the modified randomized signals with a previously stored transmission efficiency coefficient; and

sub-iteratively replacing the previously stored transmission efficiency coefficient and the previously stored randomized excitation vector with the transmission efficiency coefficient for the modified randomized signals and a corresponding modified excitation vector when the transmission efficiency coefficient for the modified randomized signals is greater than the previously stored transmission efficiency coefficient.

28. The method of claim 27, wherein the providing of the modified randomized signals for which the transmission efficiency coefficient is greater than the transmission efficiency coefficient of the randomized signals is carried out by performing a predetermined number P of sub-iterations.

29. The method of claim 28, wherein the sub-iteratively modifying of the electrical signals corresponding to the frequencies for which the transmission efficiency coefficient is less than the predetermined threshold value, is carried out by multiplying the initial

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amplitude and initial phase of each electrical signal by corresponding two modified random numbers.

30. The method of claim 29, wherein said two modified random numbers are generated by sub-iteratively adding $\pm A\beta_1 \cdot p$ and $\pm A\beta_2 \cdot p$ to the two random numbers,
5 correspondingly, where $p = 1, 2, \dots, P$.

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