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(54) Title: METHOD AND SYSTEM FOR SELECTING ANTENNAS FOR COMMUNICATION BETWEEN A RECEIVER SIDE AND A TRANSMITTER SIDE OF A WIRELESS MIMO SYSTEM

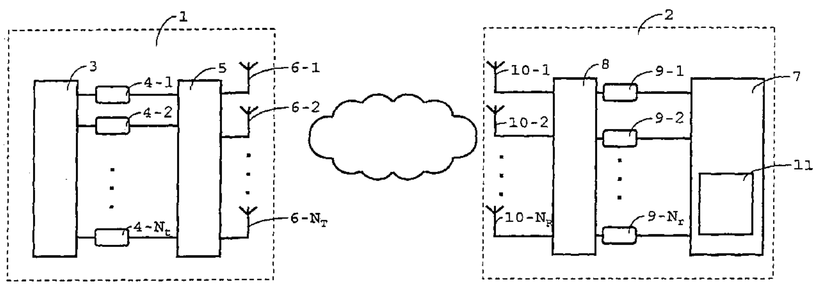


Fig. 1

(57) Abstract: A method of selecting antennas (6, 10; 32, 48-50) for communication between the receiver side and the transmitter side of a wireless MIMO system includes obtaining channel state information representative of channel transfer functions between combinations of transmitter and receiver antennas, and performing at least once an iterative algorithm for calculating an optimised parameter vector for a family of parameterised discrete probability density functions giving a higher probability to states representing a selection of antennas giving a more desirable value of a target function based on the channel state information and an optimised value of the target function calculated for at least one sample state drawn at least in part according to the probability density function obtained using the current parameter vector. At least a final performance of the iterative algorithm uses selections of both a number Nr of receiver antennas (10; 32) and a number *N*, of transmitter antennas (6; 48-50) to calculate values of the target function, so as to arrive at a selection of both a sub-set of all available transmitter antennas (6; 48-50) and a sub-set of all available receiver antennas (10; 32).

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# METHOD AND SYSTEM FOR SELECTING ANTENNAS FOR COMMUNICATION BETWEEN A RECEIVER SIDE AND A TRANSMITTER SIDE OF A WIRELESS MIMO SYSTEM

The invention relates to a method of selecting antennas for communication between a receiver side and a transmitter side of a wireless MIMO system having a number $N_R$ of receiver antennas and a switching system for causing a sub-set formed by a smaller number $N_r$ of the receiver antennas to be used for communication in connection with respective RF chains at the receiver side and having a number $N_T$ of transmitter antennas and a switching system for causing a sub-set formed by a smaller number $N_t$ of the transmitter antennas to be used for communication in connection with respective RF chains at the transmitter side, which method includes

obtaining channel state information representative of channel transfer functions between combinations of transmitter and receiver antennas, and

performing at least once an iterative algorithm for calculating

an optimised parameter vector for a family of parameterised discrete probability density functions giving a higher probability to states representing a selection of antennas giving a more desirable value of a target function based on the channel state information and

an optimised value of the target function calculated for at least one sample state drawn at least in part according to the probability density function obtained using the current parameter vector.

The invention also relates to a system for selecting antennas for communication between a receiver side and a transmitter side of a wireless MIMO system having a number $N_R$ of receiver antennas and a switching system for causing a sub-set formed by a smaller number $N_r$ of the receiver antennas to be used for communication in connection with respective RF chains at the receiver side and having a number $N_T$ of transmitter antennas and a switching system for causing a sub-set formed by a smaller number $N_t$ of the transmitter antennas to be used for communication in connection with respective RF chains at the transmitter side, which system is configured to:

obtain channel state information representative of channel transfer functions between combinations of transmitter and receiver antennas, and to

perform at least once an iterative algorithm for calculating

an optimised parameter vector for a family of parameterised discrete probability density functions giving a higher probability to states representing a selection of antennas giving a more desirable value of a target function based on the channel state information and

an optimised value of the target function calculated for at least one sample state drawn at least in part according to the probability density function obtained using the current parameter vector.

The invention also relates to a station for a wireless MIMO transmission system, the station including

a number of available antennas,

a switching system for connecting a sub-set consisting of a smaller number of the available antennas to a corresponding number of RF chains and

an antenna selection module for selecting a sub-set of available antennas to form communication paths, wherein the antenna selection module is arranged to

obtain channel state information representative of channel transfer functions between combinations of transmitter and receiver antennas, each combination being a combination of an antenna in the station and an antenna in at least one other station able to communicate with the station,

and wherein the antenna selection module is arrange to perform at least once an iterative algorithm for calculating an optimised parameter vector for a family of parameterised discrete probability density functions giving a higher probability to states representing a selection of antennas giving a more desirable value of a target function based on the channel state information and

an optimised value of the target function calculated for at least one sample state drawn at least in part according to the probability density function obtained using the current parameter vector,

wherein the station is configured to communicate information representing selections of antennas of the other station(s) to at least the station(s) including the selected antennas.

The invention also relates to a computer programme.

Liu, Y. *et al.*, "Transmit antenna sub-set selection for MIMO-OFDM wireless communication systems", retrieved from the Internet on 24 July 2007 at http://dept106.eng.ox.ac.uk/wb/pages/publications/rf-systems-and-technology.php discloses a low-complexity antenna sub-set selection algorithm based on the cross entropy optimisation method to maximise the capacity of a MIMO-OFDM system following either the capacity or the norm criteria. In the selection-based MIMO-OFDM system, only a sub-set of transmit antennas are used at each time slots. It is assumed that the antenna sub-set index is sent back to the transmitter from the receiver through an error-free and delay-free feedback channel. The antenna selection problem is transformed into a combinatorial optimisation problem. In order to maximise the channel capacity, the cross-entropy optimisation method is presented for an antenna sub-set selection at the transmitter.

A problem of the known method is that it does not optimise the channel capacity because it only arrives at a transmit antenna selection, thus disregarding certain communication channels that are available when different receiver antennas are selected.

It is an object of the invention to provide a method, system and station for achieving relatively good data rates, bit-error rates and transmission reliability that require relatively low hardware complexity for effective application.

This object is achieved by the method according to the invention, which is characterised in that at least a final performance of the iterative algorithm uses selections of both a number $N_r$ of receiver antennas and a number $N_t$ of transmitter antennas to calculate values of the target function, so as to arrive at a selection of both the sub-set of transmitter antennas and the sub-set of receiver antennas.

The use of a sub-set consisting of a smaller number of the total number of available receiver antennas and a sub-set consisting of a smaller number of the total number of available transmitter antennas decreases the hardware complexity in that fewer combinations of transmitter and receiver antennas have to be evaluated, whilst the presence of a relatively large number of available antennas allows one to achieve sufficient diversity for achieving relatively good data rates, bit-error rates and transmission reliability. By obtaining data representative of channel transfer functions between combinations of transmitter and receiver antennas, it is possible to base the selection on a target function representative of MIMO capacity. Instead of performing an exhaustive search over all states, importance sampling is used to reduce variance and make the evaluation of the target function for a state resulting in a close to optimal value of the target function more likely. Thus, fewer states have to be evaluated, reducing the complexity and therefore hardware requirements. Because the complexity is reduced, it becomes possible in at least a final performance of the iterative algorithm to uses sample states representing a selection of both a number of receiver antennas and a number of transmitter antennas to arrive at a selection of both the sub-set of transmitter antennas and the sub-set of receiver antennas. This ensures that a selection is made from the global state space, so that the optimum combination of transmitter and receiver antennas is more likely to be selected.

In an embodiment, in at least the final performance of the iterative algorithm, sample states for varying the selection of the number $N_r$ of the receiver antennas and the selection of the number $N_t$ of the transmitter antennas jointly are used.

An effect is to achieve a higher capacity. Effectively, optimisation is carried out over the space spanned by all possible channels, that is to say combinations of receiver and transmitter antennas. Due to the importance sampling, this search is also carried out relatively efficiently.

An alternative embodiment of the method includes performing the iterative algorithm once to select only one of the number $N_r$ of receiver antennas and the number $N_t$ of transmitter antennas, and

performing the iterative algorithm again to select the other of the number $N_r$ of receiver antennas and the number $N_t$ of transmitter antennas.

An effect is to reduce the complexity of the antenna selection process. In the final performance, only the selection of the receiver antennas or the selection of the transmitter antennas is varied. Effectively, a smaller part of the space spanned by all possible antenna combinations is sampled with each performance of the iterative algorithm.

An embodiment of the method includes communicating information representative of at least part of the selection of the number $N_t$ of transmitter antennas from the receiver side to the transmitter side of the wireless MIMO system, preferably using a feedback channel.

An effect is to be able to carry out selection of both transmitter and receiver antennas centrally and still be able to establish the channels in an actual communication system. By selecting both transmitter and receiver antennas centrally, the selection is as close to the optimum within the processing constraints. Communication of the information representative of at least part of the selection of the number of transmitter antennas from the receiver side to the transmitter side makes possible an implementation in which a running adaptation to changing channel conditions is carried out in a MIMO system.

In an embodiment, the iterative algorithm is a stochastic search algorithm.

An effect is to obtain a better selection in terms of the MIMO capacity where certain ones of the channels may be correlated. The iterative algorithm searches in a direction determined by the new value of the parameter vector for the family of probability density functions. The new value is based on the capacity calculated by sampling the state space containing all possible combinations of the smaller number $N_t$ of available transmitter antennas and the smaller number $N_r$ of receiver antennas in accordance with the current probability density function. Thus correlations between channels will emerge and be reflected in the parameter vector.

An embodiment of the method includes using a target function for calculating the channel capacity for selecting states for calculating a next value of the parameter vector at each iteration.

An effect is that the achieved result is closer to the theoretical optimum, also at higher values of the Signal-to-Noise ratio for the channels than if a norm-based criterion was used to calculate a next value of the parameter vector at each iteration. Because the channel capacity is dependent on the Signal-to-Noise ratio, a selection of states for calculating a next value of the parameter vector at each iteration based on the capacity directly will result in a higher channel capacity than one based only on a norm-based criterion. A criterion of the latter type in effect takes only the signal strength into account. A higher channel capacity is desirable from the point of view of lowering the bit error rate.

In an embodiment, the iterative algorithm implements a cross-entropy method, tending to minimise the Kullback-Leibler divergence between the parameterised probability density function at the current parameter vector values and an optimal probability density function.

It has been shown (e.g. in Rubinstein, R.Y. and Kroese, D.P., "The Cross-Entropy Method: A Unified Approach to Combinatorial Optimization, Monte-Carlo Simulation and Machine Learning", Springer, 2004, pp. 59-129) that such methods for solving optimisation problems have low complexity and rapid, indeed asymptotic, convergence to a solution.

In an embodiment, the number of sample states drawn at an iteration is decremented as the iterative algorithm is performed.

An effect is to start the performance of the algorithm with a wide range of samples covering as much of the space spanned by all possible antenna combinations. Robustness is therefore improved, since the method is less likely to converge to a mere local optimum. Decrementing the number of sample states lowers the complexity and speeds up the performance of the method.

In an embodiment, the target function is evaluated for a number of sample states at each iteration, and one or more sample states determined to result in best values of the target function are retained for evaluation and comparison with sample states at at least one next iteration.

An effect is to emphasise those sample states that are close to the optimum, as a consequence of which the convergence to a solution is relatively rapid.

In an embodiment, the method is performed to select one or more mobile user terminals for communication with a base station having a number $N_R$ of available antennas and a switching system for selecting a smaller number $N_r$ of the available antennas to be connected to respective RF chains.

An effect is to provide a useful implementation of a centralised selection of antennas in a MIMO system. Some of the mobile user terminals may have several antennas available for connection to a smaller number of RF chains (or only one RF chain), but it may also be the case that no selection of antennas within any one mobile user terminal is made.

According to another aspect, the system for selecting a set of communication channels between a receiver side and a transmitter side of a wireless MIMO system according to the invention is characterised in that the system is configured to use in at least a final performance of the iterative algorithm selections of both a number $N_r$ of receiver antennas and a number $N_t$ of transmitter antennas to calculate values of the target function, so as to arrive at a selection of both the sub-set of transmitter antennas and the sub-set of receiver antennas.

The system forms an antenna selection module that can be implemented with low complexity, yet yields selections of antennas that form communication paths least subject to fading.

In an embodiment, the system is configured to carry out a method according to the invention.

According to another aspect, the station for a wireless MIMO transmission system according to the invention is characterised in that the antenna selection module is arranged to use in at least a final performance of the iterative algorithm selections of both a number $N_r$ of receiver antennas and a number $N_t$ of transmitter antennas to calculate values of the target function, so as to arrive at a selection of both a sub-set of available antennas at the station and a sub-set of available antennas at the other station(s) to form the communication paths.

The station centrally selects sub-sets of available antennas at either side of a wireless MIMO system, achieving a near optimum use of the theoretical MIMO capacity.

An embodiment of the station is configured to carry out a method according to the invention.

According to another aspect of the invention, there is provided a computer programme including a set of instructions capable, when incorporated in a machine-readable medium, of causing a system having information processing capabilities to perform a method according to the invention.

The invention will be explained in further detail with reference to the accompanying drawings, in which:

Fig. 1 is a schematic diagram of a first wireless MIMO system;

Fig. 2 is a flow chart of a first antenna selection method for use in a wireless MIMO systems;

Fig. 3 is a flow chart of a second antenna selection method for use in a wireless MIMO system;

Fig. 4 is a schematic diagram of a second wireless MIMO system;

Fig. 5 is a diagram comparing the capacity achieved using various antenna selection methods in dependence on the Signal-to-Noise Ratio; and

Fig. 6 is a diagram comparing the capacity achieved using various selection methods in dependence on the number of selected antennas.

A first example of a wireless MIMO (Multiple Input and Multiple Output) system to be discussed below includes a transmitter terminal 1 and a receiver terminal 2. The nomenclature does not imply that communication between the two terminals 1,2 is one-way only; it is merely a convenient way to distinguish between the two.

The transmitter terminal includes a transmitter 3, a number $N_t$ of RF circuits 4-$i$, $i = 1,\ldots N_t$ and a switching device 5. It further includes a number $N_T$ of antennas 6-$j$, $j = 1,\ldots,N_T$, which are available for connection to the RF circuits 4. The number $N_t$ of RF circuits 4 is smaller than the number $N_T$ of antennas 6.

Similarly, the receiver terminal 2 includes a receiver 7, a number $N_r$ of RF circuits 9-$i$, $i$ = 1,...$N_r$ and a switching device 8. It further includes a number $N_R$ of antennas 10-$j$, $j$ =1,...,$N_R$, which are available for connection to the RF circuits 9. The number $N_r$ of RF circuits 9 is smaller than the number $N_R$ of antennas 106.

The $N_r$ RF circuits 9 at the receiver side and $N_t$ RF circuits 4 at the transmitter side, each connected to a different one of an array of antennas, form respective phased arrays corresponding to two adaptive antennas. The output of each RF circuit 9$j$ is multiplied by a complex weight and combined by summing. The weights are varied to improve the performance of the communication system in terms of reliability and data transmission capacity. In particular, interference can be reduced. In a known manner, space-time coding can be implemented to improve the data transmission capacity, by transmitting data via separate radiation patterns within a common region of the spectrum. This assumes that the radiation patterns to not interfere, i.e. that the channels between transmitter and receiver antennas are independent. By providing relatively large numbers $N_T$, $N_R$ of antennas 6,10, the likelihood thereof is increased. However, the complexity and cost of the transmitter terminal 1 and receiver terminal 2 would be relatively high if the number of RF circuits 4,9 would also be high. For example, the derivation of the optimum weights to be given to the outputs, as well as the combination and multiplexing operations would be computationally demanding. By selecting smaller numbers $N_t$, $N_t$ of the available antennas 6,10 for connection to the RF circuits 4,9, relatively good performance in terms of data rate, bit-error rates and transmission reliability can still be achieved, but at relatively low costs and with relatively low hardware complexity. A diversity order close to that of a system using all available antennas is achievable when selecting only a sub-set of the available antennas. Using a selection method as outlined below, an antenna selection module 11 selects the best sub-set of communication channels formed by combinations of transmitter antenna 6 and receiver antenna 10.

The antenna selection module 11 uses an iterative algorithm (Fig. 2, 3) to arrive at an optimum sub-set of all possible communication channels in a computationally efficient manner. This algorithm uses sample states representing selections of $N_r$ receiver antennas 10 and/or selections of $N_t$ transmitter antennas 6, whilst avoiding an exhaustive search of the sample state space representing all possible antenna combinations. At least a final performance of the iterative algorithm uses sample states representing a selection of both a number $N_r$ of receiver antennas 10 and a number $N_t$ of transmitter antennas 6. Thus, the sub-sets of receiver antennas 10 and transmitter antennas 10 are both selected centrally, by the one antenna selection module 11. As a result, the transmitter terminal 1 is less complex. Moreover, a result closer to optimum is achievable, since the search for an optimal set of channels is carried out over a large sample state space, as opposed to merely a sub-set thereof.

The selection algorithm is based on the transformation of the antenna selection problem into a combinatorial optimisation problem, and to do so efficiently. Because it is a stochastic search algorithm by nature, it is not restricted by channel conditions. It can be used not only for independent channels, but also for correlated channels.

In a wireless MIMO system with $N_T$ transmit antennas and $N_R$ receiver antennas, the received signal is:

$$\mathbf{y} = \sqrt{\frac{E_s}{N_T}} H\mathbf{s} + \mathbf{v}\,, \qquad (1)$$

where $\mathbf{y} = [y_1, \ldots, y_{NR}]$ is the received signal vector and $\mathbf{s}$ is the transmitted signal vector. $E_s$ is the total transmitted energy and $\mathbf{v}$ is a complex

Gaussian noise vector, assumed to have independently and identically distributed entries with zero mean and unit variance.

The channel matrix $H$ is an $N_R \times N_T$ complex matrix, of which the entries $h_{ij}$ represent the transfer function between the $i$th receiver antenna 10-$i$ and the $j$th transmitter antenna 6-$j$. The transfer functions are dependent on the channel fading coefficients for the channels between the $i$th receiver antenna and the $j$th transmitter antenna. The elements $h_{ij}$ of the channel matrix are independent zero-mean unit-variance complex Gaussian variables. The channel matrix $H$ represents channel state information.

Fig. 2 illustrates a joint antenna selection algorithm as carried out by the antenna selection module 11 to set up or adjust the communication between the transmitter terminal 1 and the receiver terminal 2. In a first step 12, channel state information representative of the channel fading coefficients, and thus the channel matrix $H$, is obtained. Methods of obtaining channel state information of this type are known *per se*, e.g. from Paulraj, A. *et al.*, "Introduction to Space-Time Wireless Communications", Cambridge University Press, 2003. As an example, pilot symbols can be transmitted from each transmitter antenna 6 and picked up at each receiver antenna 10.

The set $\Omega$ of all possible combinations of antennas has $Q = Q_R \times Q_T$ members, where $Q_R = \binom{N_R}{N_r}, Q_T = \binom{N_T}{N_t}$, and can be written as $\Omega = (\omega_1, \ldots \omega_Q)$. The indicators of a selection of receiver and transmitter antennas 6,10 can be written as: $\omega = (\omega_{qR}; \omega_{qT})$. Thus, for example, if the first, fourth, fifth and eighth antennas are selected out of eight receiver antennas 10 and the third, fifth and sixth antennas are selected out of six transmitter antennas 6, then $\omega$ will be {1,4,5,8;3,5,6}.

The method of Fig. 2 is configured to optimise a target function $S(\omega)$, more particularly to solve the combinatorial optimisation problem:

$$r^* = \arg\max_{\omega\in\Omega} S(\omega), \tag{2}$$

where $r^*$ denotes the global optimum of the objective function $S(\omega)$, which is proportional to the channel capacity associated with the selection.

The channel capacity, also referred to herein as the MIMO capacity, is calculated as follows:

$$C^{(\omega)}\left(H^{(\omega)}\right) = {}^2\log\left(\det\left(I_{N_{\min}^{(\omega)}} + \frac{\eta}{N_T} G^{(\omega)}\right)\right). \tag{3}$$

In eq. (3), $\eta$ is the average signal-to-noise ratio, and $I_{Nmin}$ is the $N_{min} \times N_{min}$ identity matrix, whereas the matrix $G^{(\omega)}$ is defined as:

$$G^{(\omega)} = \begin{cases} \left(H^{(\omega)}\right)^H H^{(\omega)} & \text{if} \quad N_R > N_T \\ H^{(\omega)}\left(H^{(\omega)}\right)^H & \text{if} \quad N_T > N_R \end{cases}, \tag{4}$$

$(\bullet)^H$ being used to denote the Hermitian transpose or adjoint. $H^{(\omega)}$ denotes the matrix composed of columns and rows selected from $H$ as indexed by $\omega_{qT}$ and $\omega_{qR}$. It is observed that, in an alternative embodiment to the method illustrated in Fig. 2, the target function that is optimised (minimised) is the trace of $G$, i.e. the Frobenius norm of $H$.

The method of Fig. 2 makes use of a family of probability density functions for a Bernoulli process:

$$f(\omega;\mathbf{p}) = f(\omega_R;\mathbf{p}_R)\cdot f(\omega_T;\mathbf{p}_T), \tag{5}$$

parameterised by the parameter vector $p$ = $[p_R;p_T]$.

One can define a stochastic estimation of the probability that the target function has a higher value than some threshold $r$:

$$l(r) = \sum_{\omega \in \Omega} I_{\{S(\omega \geq r)\}} f(\omega; v), \tag{6}$$

in which $I_{\{\cdot\}}$ is the indicator function. $l$ can be estimated by means of importance sampling, using an importance distribution $g(\omega)$:

$$\hat{l} = \frac{1}{N} \sum_{n=1}^{N} I_{\{S(\omega^{(n)}) \geq r\}} \frac{f(\omega^{(n)}; \mathbf{v})}{g(\omega^{(n)})}. \tag{7}$$

An optimal value for the importance distribution is:

$$g^*(\omega) = \frac{I_{\{S(\omega) \geq r\}} f(\omega; v)}{l} \tag{8}$$

The method illustrated in Fig. 2 seeks to find a parameter vector $\boldsymbol{p}^*$, such that the Kullback-Leibler divergence between $g^*$ and $f(\omega;\boldsymbol{p}^*)$ is minimal, where the Kullback-Leibler divergence between two probability functions $g,f$ is defined as:

$$E\left[\ln\left(\frac{g(x)}{f(x)}\right)\right] = \int g(x)\ln(g(x))dx - \int g(x)\ln(f(x))dx. \tag{9}$$

In the joint antenna selection method of Fig. 2, after the step 12 of obtaining the channel state information representative of channel fading coefficients between combinations of transmitter and receiver antennas 6,10, the parameter vector $\boldsymbol{p}$ is given (step 13) an initial value $\boldsymbol{p}^{(0)} = 1/2$. An iteration counter $t$ is set at $t := 1$.

The probability density function $f(\omega;\boldsymbol{p}^{(t-1)})$ will be used to draw a number $N$ of sample states $\omega^{(1)}, \omega^{(2)}, \ldots, \omega^{(N)}$ at each iteration (step 14). In the illustrated method, this number $N$ is made large at the start of execution of the method and decremented as the iteration count $t$ increases. Moreover, a smoothing factor $\lambda$ is used to modify (step 15) the parameter vector $p^{(t)}$ calculated (step 16) at the current iteration, using the result of the previous iteration, according to:

$$\mathbf{p}^{(t)} := \lambda \cdot \mathbf{p}^{(t)} + (1-\lambda) \cdot \mathbf{p}^{(t-1)}. \tag{10}$$

For this reason, after the step 13 of initialising the parameter vector $\boldsymbol{p}$, values for the number $N$ of sample states to draw at the current iteration and the smoothing factor $l$ to apply are determined (step 17).

In the next step 14, the $N$ sample states are generated from the probability density function at the current parameter vector value. Suitable methods for generating the $N$ sample states using the current value of the probability density function are known. Any random sample method would be suitable. More details can be found in Liu, J., "Monte Carlo Strategies in Scientific Computing", New York, Springer, 2001. In order to avoid that the best samples at each iteration are flooded by other samples, a method called elite strategy is applied in the illustrated embodiment. An elite set is defined, which is generally empty at initialisation. At each iteration, $N_{elite}$ sample states $\omega^{(i)}$ are copied to the elite set. The sample states in the current elite set are added to the $N$ samples drawn according to the current value of the probability function $f(\omega;\boldsymbol{p}^{(t)})$. Thus, $N_{elite}$ sample states determined to result in best values of the target function $S(\omega^{(n)})$ are retained for evaluation and comparison with sample states at at least one next iteration, assuming that there is a next iteration.

A subsequent step 18, implements a replacement strategy. Invalid samples $\omega^{(i)}$ drawn in the preceding step 14 are replaced by new, valid ones. This step takes account of the algorithm's stochastic nature, which can result in a sample state with, for example more receiver antennas 10 than the number $N_r$ of RF chains 9 at the receiver terminal 2.

Having assembled a valid set of newly drawn and elite sample states $\omega^{(i)}$, the values of the target function $S(\mathrm{w})$ are calculated (step 19) for each of them, to give a set:

$$\left\{S\left(\omega^{(n,t)}\right)\right\}_{n=1}^{N}. \tag{11}$$

The values in the set are ordered, and the (1-$\rho$) sample quantile $-\rho$ is a parameter determining how many important samples will be used to update the parameter vector **p** - of the performances is determined (step 20):

$$r^{(t)} = S_{(\lceil(1-\rho)N\rceil)}. \tag{12}$$

It is also convenient to carry out the reservation of the $N_{elite}$ best samples at this stage 20. $N_{elite}$ will be between 10 % and 20 % of the total number $N$ of samples at the current iteration. The choice of value for $\rho$ will affect the conversion rate. A value within the range [0.9,0.95] will generally be sufficient to guarantee convergence. Reference is made to Rubinstein, R.Y. and Kroese, D.P., "The Cross-Entropy Method: A Unified Approach to Combinatorial Optimization, Monte-Carlo Simulation and Machine Learning", Springer, 2004, pp. 29-59 for further details on how to arrive at an appropriate value for $\rho$.

Subsequently (step 16), the parameter vector $\boldsymbol{p}$ is updated as follows:

$$\widehat{p}_i^{(t)} = \frac{\sum_{n=1}^{N} I_{\left\{S\left(\omega^{(n,t)}\right)\geq r^{(t)}\right\}} I_{\{\alpha_i\}}\left(\omega_{q_R}^{(n,t)}\right) I_{\{\beta_i\}}\left(\omega_{q_T}^{(n,t)}\right)}{\sum_{n=1}^{N} I_{\left\{S\left(\omega^{(n,t)}\right)\geq r^{(t)}\right\}}}. \tag{13}$$

In eq. (13), $\alpha_i$ is the number of the $i^{\text{th}}$ receiver antenna 10-$i$, and $\beta_j$ is the number of the $j^{\text{th}}$ transmitter antenna 6-$j$.

If a stopping criterion is not satisfied, then the iteration parameter is updated to $t := t+1$, and the step 15 of smoothing the parameter vector is carried out, after which the steps 17,14,18,19,20,16 detailed above are carried out again.

In one embodiment, the stopping criterion is that $\boldsymbol{p}^{(t)}$ has not changed for a number of successive iterations $t$. In another embodiment, the stopping criterion is that the probability density function (which is a discrete probability density function that generally corresponds to the current value of $\boldsymbol{p}$) at the current value of the parameter vector $\boldsymbol{p}^{(t)}$ is a degenerate, i.e. binary vector. Other stopping criteria are possible.

Having determined the optimised value of the parameter vector $\boldsymbol{p}$, and thus the corresponding probability density function, a sample state is determined in accordance with this value of the probability density function. This sample state represents a selection of $N_r$ receiver antennas 10 and $N_t$ transmitter antennas 6. Information representative of the selection of the number $N_t$ of transmitter antennas 6 is transmitted (step 21) by the receiver 7 to the transmitter 3 using a feedback channel. At the transmitter terminal 1, this information is used to reconfigure the switching device 5. To avoid interference, the transmitter 3 is quiet during this period. Alternatively, the feedback link can be differentiated from feed-forward links by frequency or code orthogonality. After reconfiguration, the training or handshake period during which the antennas 6, 10 are selected and connected is over, and normal data transmission can resume.

It is observed that an alternative to the Cross-Entropy method detailed above is one in which the iterative algorithm is an adaptive Markov Chain Monte Carlo method. Such a method is also a stochastic simulation technique for exploring a probability distribution of interest. It also represents the feasible solution space by a probability distribution that is updated during simulations. Briefly, a variant of such a method runs as follows. Let the proposal density function be denoted as $q(\omega;\boldsymbol{p})$ and $r^{(t)}$ be a series of decreasing step sizes with $t$ the value of the iteration counter:

1) Initialise $\omega^{(0)}$ at random or deterministically, set a current best estimate $\widehat{\omega}^{*}$ at $\omega^{(0)}$, and set $\boldsymbol{p}^{(0)}$ at an initial value $p_j^{(0)} = 1/2$, $j = 1,\dots,N_t + N_r$.

2) Draw a set of $N$ sample states using the proposal density function $q(\omega;\boldsymbol{p}^{(t-1)})$. Suitable methods for generating $N$ sample states using the current value of the proposal density method are known, e.g. the Metropolis-Hastings method.

3) Update the parameter vector $\boldsymbol{p}$ as follows:

$$p^{(t+1)} = p^{(t)} + r^{(t+1)}\left(\frac{1}{N}\sum_{n=1}^{N}\left[\omega^{(n)}\right] - p^{(t)}\right).$$

4) If $S(\omega^{(n)}) > S(\widehat{\omega}^{*})$, $n = 1, \dots, N$, then $\widehat{\omega}^{*} := \omega^{(n)}$.

5) If the stopping criterion has not been reached, repeat from step 2). A good stopping criterion in this case is a maximum number of iterations.

Fig. 3 illustrates a variant of the method of Fig. 2. In this variant, the iterative algorithm described in detail with regard to Fig. 2 is performed once to determine only one of two parts $\boldsymbol{p}_r$, $\boldsymbol{p}_t$ of the probability vector $\boldsymbol{p}$. The parts relate to the number $N_r$ of receiver antennas 10 and the number $N_t$ of transmitter antennas 6, respectively. The iterative algorithm is performed again to determine the other of the two parts $\boldsymbol{p}_r$, $\boldsymbol{p}_t$, but with the values of the first of the two parts as just calculated. Thus, the final performance of the iterative algorithm uses sample states representing a selection of both a number $N_r$ of receiver antennas 10 and a number $N_t$ of transmitter antennas 6, although the selection of either the set of transmitter antennas 6 or the set of receiver antennas 10 remains static throughout the final performance of the iterative algorithm. Because of the staged selection, the method is referred to herein as a sequential selection method.

In more detail, in a first step 22, the channel state information representative of channel fading coefficient between combinations of the $N_R$ receiver antennas 10 and $N_T$ transmitter antennas 6 is obtained by the antenna selection module 11. This is done in the same way as in the corresponding step 12 in the joint selection method of Fig. 2.

On the assumption that the $N_r$ receiver antennas 10 are selected first, the first part $\boldsymbol{p}_R$ of the parameter vector, for a family of parameterised probability functions $f(\omega_{qR};\boldsymbol{p}_R)$ is initialised (step 23). In a next step 24, the $N_r$ receiver antennas 10 are selected using a method as outlined in Fig. 2, but only by searching the state space containing all $\binom{N_R}{N_r}$ possible selections $\omega_{qR}$ of receiver antennas 10.

Disregarding the use of an elite set, smoothing parameter $\lambda$ and varying number $N$ of sample states $\omega_{qR}$, this step 24 proceeds as follows:

1) Start with the initial value $\boldsymbol{p}_R^{(0)} = ½$, set in the preceding step 23, and set the iteration counter $t$ at $t := 1$.

2) Generate $N$ samples $\omega^{(1)}{}_{qR}$, $\omega^{(2)}{}_{qR}$, $\omega^{(3)}{}_{qR}$, ..., $\omega^{(N)}{}_{qR}$, using the probability density function $f(\omega;\boldsymbol{p}_R^{(t-1)})$.

3) Calculate the target function values $\left\{S\left(\omega_{q_R}^{(n,t)}\right)\right\}_{n=1}^{N}$ and order them from smallest to largest. Select a sample quantile $r^{(t)}$ of the performances $r^{(t)} = S_{(\lceil(1-\rho)N\rceil)}$.

4) Update $p_R^{(t)}$ according to:

$$\widehat{p}_{R,i}^{(t)} = \frac{\sum_{n=1}^{N} I_{\{S(\omega_{qR}^{(n,t)} \geq r^{(t)})\}} I_{\{\alpha_i\}}\left(\omega_{qR}^{(n,t)}\right)}{\sum_{n=1}^{N} I_{\{S(\omega_{qR}^{(n,t)} \geq r^{(t)})\}}}.$$

5) Evaluate the stopping criterion and repeat steps 2)-4) if necessary.

In the above, the target function is calculated according to eq. (3) and (4), but with the sub-matrix $H^{(\omega)}$ being the sub-matrix of $H$ comprised of all $N_T$ columns and the $N_r$ rows indicated by $\omega^{(n)}{}_{qR}$.

The result of this step 24 is an optimal receiver antenna subset $\omega^{*}{}_{qR}$.

A next step 25 is to initialise the second part $p_T$ of the parameter vector $p$, for use in finding an optimal one of a family of parameterised probability functions $f(\omega_{qT};p_T)$. Next (step 26), the $N_t$ transmitter antennas 6 are selected as follows:

1) Start with the initial value $p_T^{(0)} = ½$, set in the preceding step 25, and set the iteration counter $t$ at $t := 1$.

2) Generate $N$ samples $\omega^{(1)}{}_{qT}$, $\omega^{(2)}{}_{qT}$, $\omega^{(3)}{}_{qT}$, ..., $\omega^{(N)}{}_{qT}$, using the probability density function $f(\omega;p_T^{(t-1)})$.

3) Calculate the target function values $\left\{S\left(\omega_{qT}^{(n,t)}\right)\right\}_{n=1}^{N}$ and order them from smallest to largest. Select a sample quantile $r^{(t)}$ of the performances $r^{(t)} = S_{(\lceil(1-\rho)N\rceil)}$.

4) Update $p_T^{(t)}$ according to:

$$\widehat{p}_{T,i}^{(t)} = \frac{\sum_{n=1}^{N} I_{\{S(\omega_{qT}^{(n,t)} \geq r^{(t)})\}} I_{\{\beta_i\}}\left(\omega_{qT}^{(n,t)}\right)}{\sum_{n=1}^{N} I_{\{S(\omega_{qT}^{(n,t)} \geq r^{(t)})\}}}.$$

5) Evaluate the stopping criterion and repeat steps 2)-4) if necessary.

In the above, the target function is calculated according to eq. (3) and (4), but with the sub-matrix $H^{(\omega)}$ being the sub-matrix of $H$ comprised of the $N_t$ columns determined by $\omega^{(n)}{}_{qT}$ and the $N_r$ rows indicated by $\omega^{*}{}_{qR}$. Thus, the second performance of the iterative algorithm uses selections of both a number $N_r$ of receiver antennas and a number $N_t$ of transmitter antennas to calculate values of the target function $S(\omega)$, so as to arrive at a selection of both the sub-set of transmitter antennas 6 and the sub-set of receiver antennas 10.

Finally, in a step 27 corresponding to the last step 21 in the method of Fig. 2, information representative of the selection of the number $N_t$ of transmitter antennas 6 is sent from the receiver terminal 2 to the transmitter terminal 1.

A variant of the joint selection method or the sequential selection method can be used in an uplink multi-user system as illustrated schematically in Fig. 4. A base station 28 includes a receiver 29, a number $N_r$ of RF circuits 30-$i$, $i = 1,...N_r$ and a switching device 31. It further includes a number $N_R$ of antennas 32-$j$, $j = 1,...,N_R$, which are available for connection to the RF circuits 30. The number $N_r$ of RF circuits 30 is smaller than the number $N_R$ of antennas 32.

Each of first, second and third mobile user terminals 33-35 includes a transmitter 36-38, two RF circuits 39-44, and a switching device 45-47. They each also include three antennas 48a-48c, 49a-49c, 50a-50c, which are available for connection to the respective RF circuits 39-44. The total number (six) of RF circuits at the receiver side of the uplink multi-user system is smaller than the number $N_T = 9$ of antennas, in this example. However, this need not be the case.

The base station 28 includes an antenna selection module 51, configured to use the joint or sequential antenna selection method in order to select which $N_r$ of the antennas 32 of the base station 28 to connect to the RF circuits 30. This antenna selection module 51 also selects a smaller number $N_t$ of all $N_T$ available antennas 48-50 at the mobile user terminals 33-35 for forming communication paths between the base station 28 and fewer than all of the user terminals 33-35. Thus, a method such as the ones outlined in Fig. 2 and 3 is performed to select one or more of the mobile user terminals 33-35 for communication with the base station 28. The step 18 in the method of Fig. 2 in which the sample states drawn in accordance with the probability density function are checked for compliance with rules may be modified to ensure that a sufficient number of antennas 48-50 is selected at each mobile user terminal 33-35, or that only all antennas 48-50 of any one user terminal 33-35 can be chosen. Alternatively, where the mobile user terminals 33-35 are not provided with the switching devices 45-47, the probability density function may be modified and the matrix $H$ representative of the channel matrix may be modified to perform the calculation of the target function $S(\omega)$ in such a manner as to reflect the fact that only all antennas 48-50 of any one of the mobile user terminals 33-35 can be selected for communication with the base station 28.

The methods described above, including those illustrated in Figs. 2 and 3 and variants using the Frobenius norm of the channel matrix $H$ are characterised by their low complexity order, leading to rapid convergence. The methods illustrated in Figs. 2 and 3 have complexity order $O(NtL^3)$, where $L = N_r = N_t$. Compared to exhaustive search strategies, the method according to Fig. 2 achieves more than 99 % of the maximum capacity, and a method as illustrated in Fig. 3 more than 95 %.

Figs. 5 and 6 plot the 10 % outage capacity for various selection methods against the Signal-to-Noise Ratio and numbers $N_r = N_t$ of selected antennas, respectively. In these drawings, "Optimal Selection" is the result obtained using a (prohibitively expensive) exhaustive search strategy; CCB is a method according to Fig. 2; SCB is a method according to Fig. 3; CNB is a method according to Fig. 2 using the Frobenius norm of the channel matrix $H$ as the target function to be optimised (maximised); and SNB is a method as illustrated in Fig. 3 using the Frobenius norm of the channel matrix $H$ as the target function to be optimised. To obtain Fig.5, the number $N_R$ of receiver antennas 10 available for selection and the number $N_T$ of transmitter antennas 6 available for selection was set at eight. The number $N_t$ of selected transmitter antennas 6 and the number $N_r$ of selected receiver antennas 10 was set at four. 10,000 different channel realisations based on computer simulations were used to obtain these results. They demonstrate the potential of the methods described above to arrive at near-optimum antenna selections.

The invention is not limited to the embodiments described above, but may be varied within the scope of the accompanying claims. For example, the method may be applied in any kind of wireless systems using MIMO techniques, such as fourth-generation (4G) wireless communication systems, co-operative communication systems, intelligent vehicle systems, netted radar, etc.

# CLAIMS

1. Method of selecting antennas (6,10;32,48-50) for communication between a receiver side and a transmitter side of a wireless MIMO system having a number $N_R$ of receiver antennas (10;32) and a switching system (8;31) for causing a sub-set formed by a smaller number $N_r$ of the receiver antennas (10;32) to be used for communication in connection with respective RF chains (9;30) at the receiver side and having a number $N_T$ of transmitter antennas (6;48-50) and a switching system (5;45-47) for causing a sub-set formed by a smaller number $N_t$ of the transmitter antennas (6;48-50) to be used for communication in connection with respective RF chains (4;39,40-44) at the transmitter side, which method includes

obtaining channel state information representative of channel transfer functions between combinations of transmitter and receiver antennas, and

performing at least once an iterative algorithm for calculating

an optimised parameter vector for a family of parameterised discrete probability density functions giving a higher probability to states representing a selection of antennas giving a more desirable value of a target function based on the channel state information and

an optimised value of the target function calculated for at least one sample state drawn at least in part according to the probability density function obtained using the current parameter vector, characterised in that

at least a final performance of the iterative algorithm uses selections of both a number $N_r$ of receiver antennas (10;32) and a number $N_t$ of transmitter antennas (6;48-50) to calculate values of the target function, so as to arrive at a selection of both the sub-set of transmitter antennas (6;48-50) and the sub-set of receiver antennas (10;32).

2. Method according to claim 1, wherein, in at least the final performance of the iterative algorithm, sample states for varying the selection of the number $N_r$ of the receiver antennas (10;32) and the selection of the number $N_t$ of the transmitter antennas (6;48-50) jointly are used.

3. Method according to claim 1, including
performing the iterative algorithm once to select only one of the number $N_r$ of receiver antennas (10;32) and the number $N_t$ of transmitter antennas (6;48-50), and
performing the iterative algorithm again to select the other of the number $N_r$ of receiver antennas (10;32) and the number $N_t$ of transmitter antennas (6;48-50).

4. Method according to any one of claims 1-3, including
communicating information representative of at least part of the selection of the number $N_t$ of transmitter antennas (6;48-50) from the receiver side to the transmitter side of the wireless MIMO system, preferably using a feedback channel.

5. Method according to any one of the preceding claims, wherein the iterative algorithm is a stochastic search algorithm.

6. Method according to any one of the preceding claims, including using a target function for calculating the channel capacity for selecting states for calculating a next value of the parameter vector at each iteration.

7. Method according according any one of the preceding claims, wherein the iterative algorithm implements a cross-entropy method, tending to minimise the Kullback-Leibler divergence between the parameterised

probability density function at the current parameter vector values and an optimal probability density function.

8. Method according to any one of the preceding claims, wherein the number of sample states drawn at an iteration is decremented as the iterative algorithm is performed.

9. Method according to any one of the preceding claims, wherein the target function is evaluated for a number of sample states at each iteration, and wherein one or more sample states determined to result in best values of the target function are retained for evaluation and comparison with sample states at at least one next iteration.

10. Method according to any one of the preceding claims, wherein the method is performed to select one or more mobile user terminals (33-35) for communication with a base station (28) having a number $N_R$ of available antennas (32) and a switching system (31) for selecting a smaller number $N_r$ of the available antennas (32) to be connected to respective RF chains (30).

11. System for selecting antennas (6,10;32,48-50) for communication between a receiver side and a transmitter side of a wireless MIMO system having a number $N_R$ of receiver antennas (10;32) and a switching system (8;31) for causing a sub-set formed by a smaller number $N_r$ of the receiver antennas (10;32) to be used for communication in connection with respective RF chains (9;30) at the receiver side and having a number $N_T$ of transmitter antennas (6;48-50) and a switching system (5;45-47) for causing a sub-set formed by a smaller number $N_t$ of the transmitter antennas (6;48-50) to be used for communication in connection with respective RF chains (4;39-44) at the transmitter side, which system is configured to:

obtain channel state information representative of channel transfer functions between combinations of transmitter and receiver antennas, and to

perform at least once an iterative algorithm for calculating

an optimised parameter vector for a family of parameterised discrete probability density functions giving a higher probability to states representing a selection of antennas giving a more desirable value of a target function based on the channel state information and

an optimised value of the target function calculated for at least one sample state drawn at least in part according to the probability density function obtained using the current parameter vector, characterised in that

the system is configured to use in at least a final performance of the iterative algorithm selections of both a number $N_r$ of receiver antennas (10;32) and a number $N_t$ of transmitter antennas (6;48-50) to calculate values of the target function, so as to arrive at a selection of both the sub-set of transmitter antennas (6;48-50) and the sub-set of receiver antennas (10;32).

12. System according to claim 11, configured to carry out a method according to any one of claims 1-10.

13. Station for a wireless MIMO transmission system, the station including

a number of available antennas (10;32),

a switching system (8;31) for connecting a sub-set consisting formed by a smaller number of the available antennas (10;32) to a corresponding number of RF chains (9,30) and

an antenna selection module (11;51) for selecting a sub-set of available antennas (10;32) to form communication paths, wherein the antenna selection module (11;51) is arranged to obtain channel state information representative of channel transfer functions between combinations of transmitter and receiver antennas, each combination being a combination of an antenna (10;32) in the station and an antenna 6;48-50) in at least one other station (1;33-35) able to communicate with the station,

and wherein the antenna selection module (11,51) is arrange to perform at least once an iterative algorithm for calculating

an optimised parameter vector for a family of parameterised discrete probability density functions giving a higher probability to states representing a selection of antennas giving a more desirable value of a target function based on the channel state information and

an optimised value of the target function calculated for at least one sample state drawn at least in part according to the probability density function obtained using the current parameter vector,

wherein the station is configured to communicate information representing selections of antennas of the other station(s) (1;33-35) to at least the station(s) (1;33-35) including the selected antennas (6;48-50),

characterised in that

the antenna selection module (11;51) is arranged to use in at least a final performance of the iterative algorithm selections of both a number $N_r$ of receiver antennas (10;32) and a number $N_t$ of transmitter antennas (6;48-50) to calculate values of the target function, so as to arrive at a selection of both a sub-set of available antennas at the station and a sub-set of available antennas (6;48-50) at the other station(s) (1;33-35) to form the communication paths.

14. Station according to claim 13, configured to carry out a method according to any one of claims 1-10.

15. Computer programme including a set of instructions capable, when incorporated in a machine-readable medium, of causing a system having

information processing capabilities to perform a method according to any one of claims 1-10.

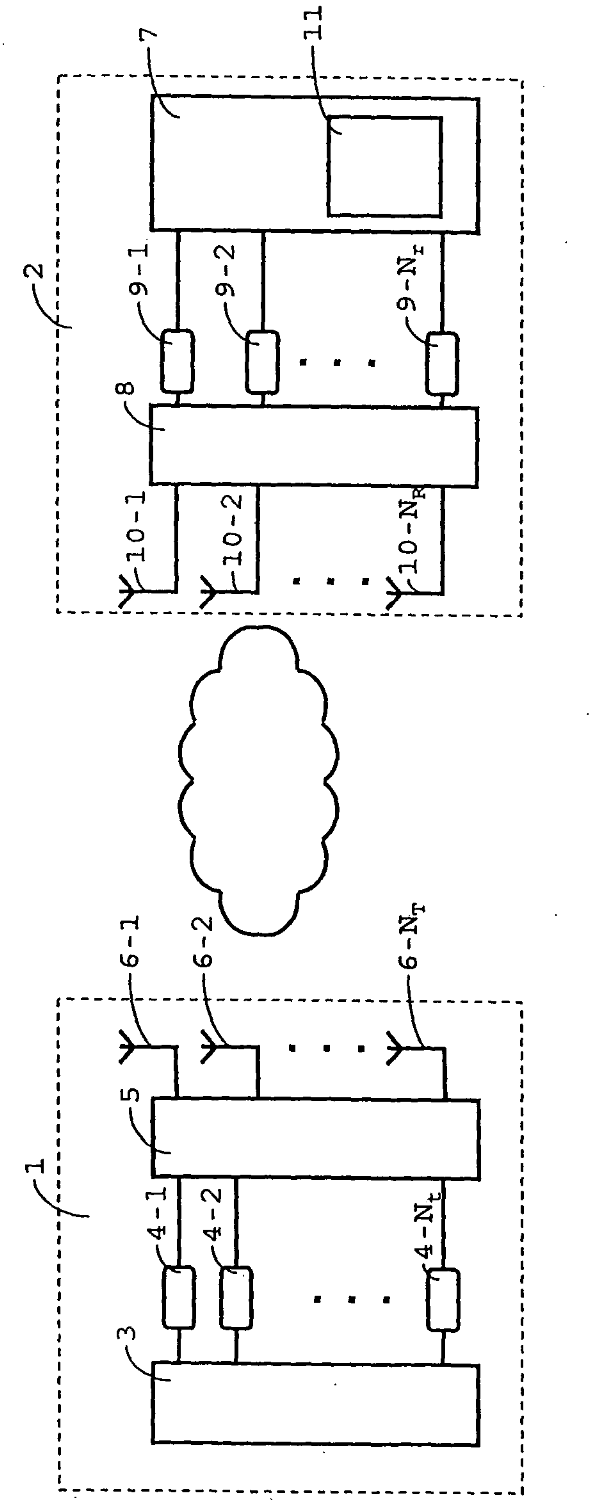


Fig. 1

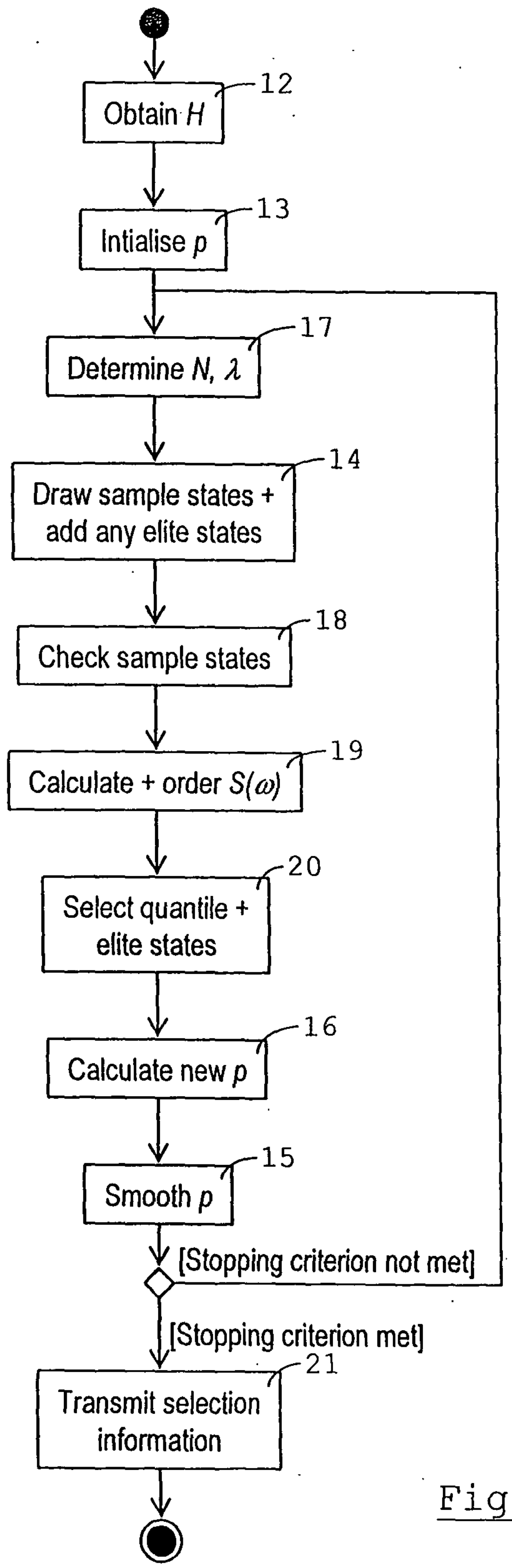
Obtain H
12
Intialise p
13
Determine N, λ
17
Draw sample states + add any elite states
14
Check sample states
18
Calculate + order S(ω)
19
Select quantile + elite states
20
Calculate new p
16
Smooth p
15
[Stopping criterion not met]
[Stopping criterion met]
Transmit selection information
21

Fig. 2

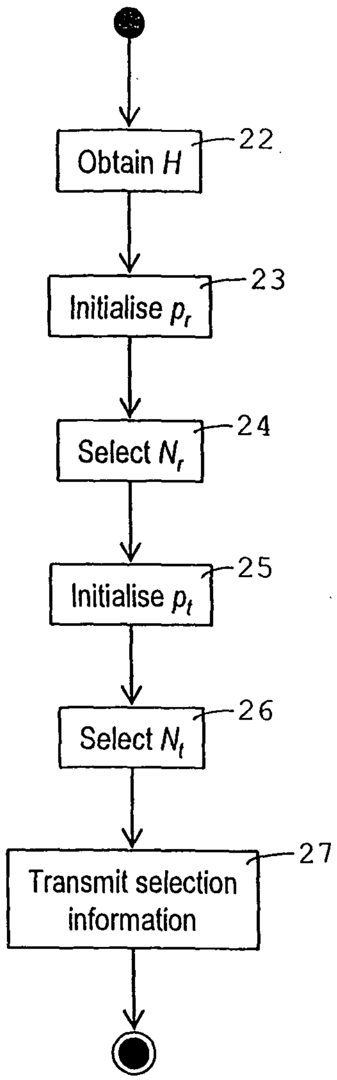
Obtain $H$
22
Initialise $p_r$
23
Select $N_r$
24
Initialise $p_t$
25
Select $N_t$
26
Transmit selection information
27

Fig. 3

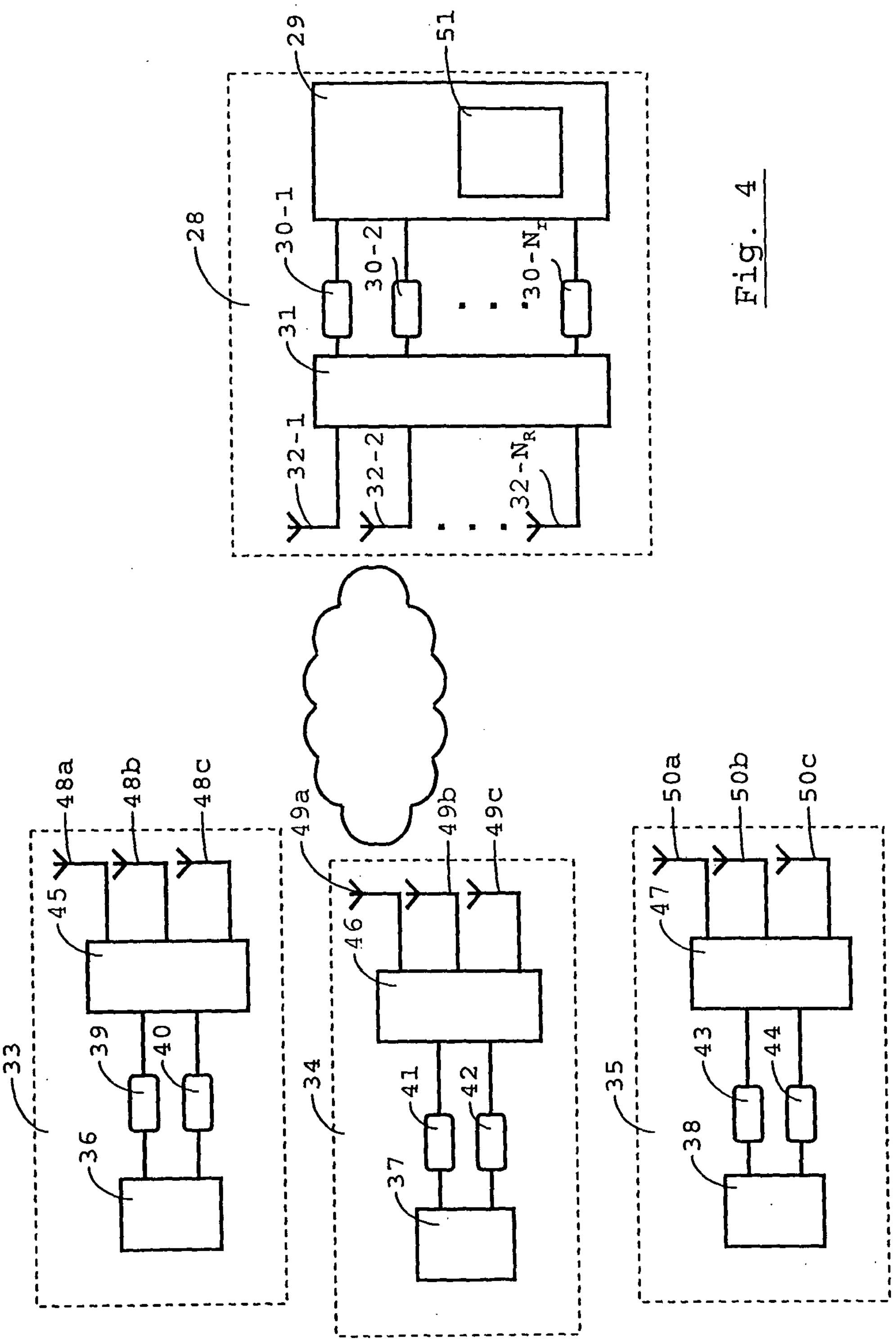
28
29
51
30-1
30-2
30-$N_T$
31
32-1
32-2
32-$N_R$
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48a
48b
48c
49a
49b
49c
50a
50b
50c

Fig. 4

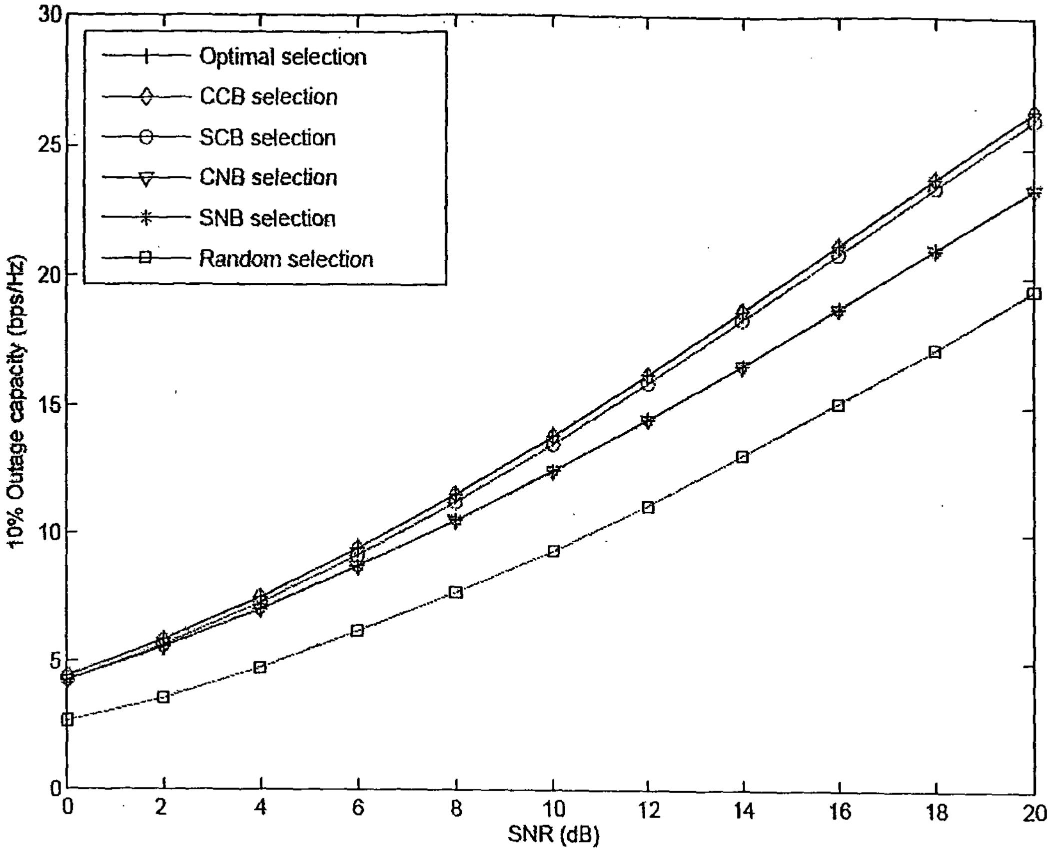
Optimal selection
CCB selection
SCB selection
CNB selection
SNB selection
Random selection
10% Outage capacity (bps/Hz)
SNR (dB)
0
5
10
15
20
25
30
0
2
4
6
8
10
12
14
16
18
20

Fig. 5

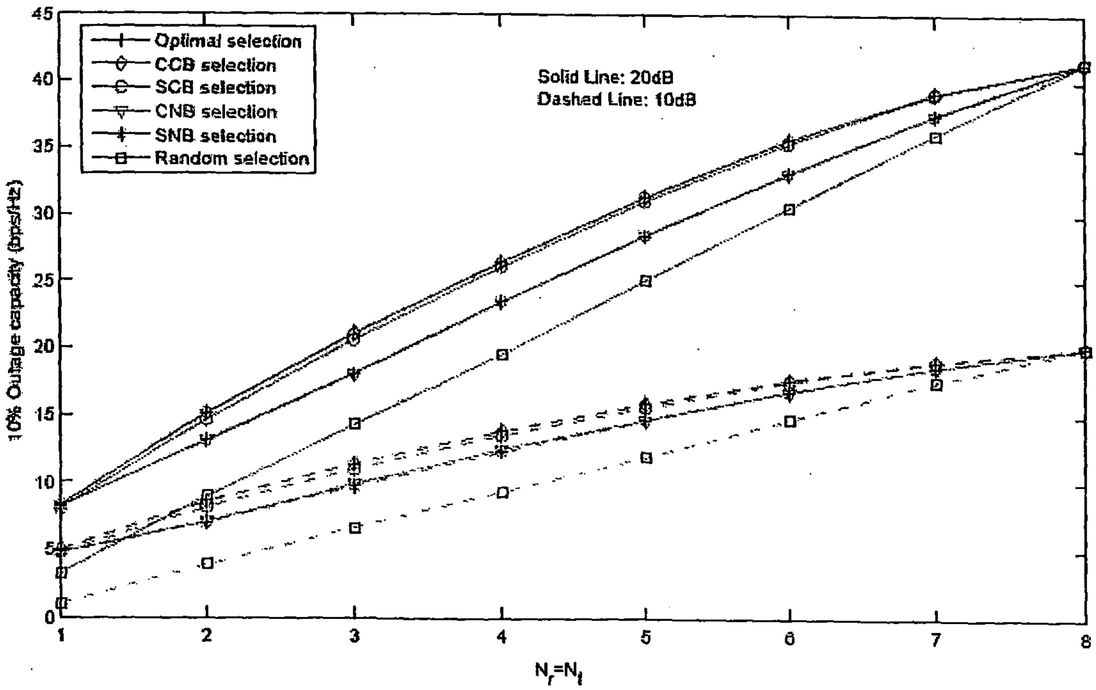
Optimal selection
CCB selection
SCB selection
CNB selection
SNB selection
Random selection
Solid Line: 20dB
Dashed Line: 10dB
10% Outage capacity (bps/Hz)
$N_r=N_t$
0
5
10
15
20
25
30
35
40
45
1
2
3
4
5
6
7
8

Fig. 6