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(54) **Title:** CONTROL DEVICE, NETWORK NODE AND METHODS THEREOF

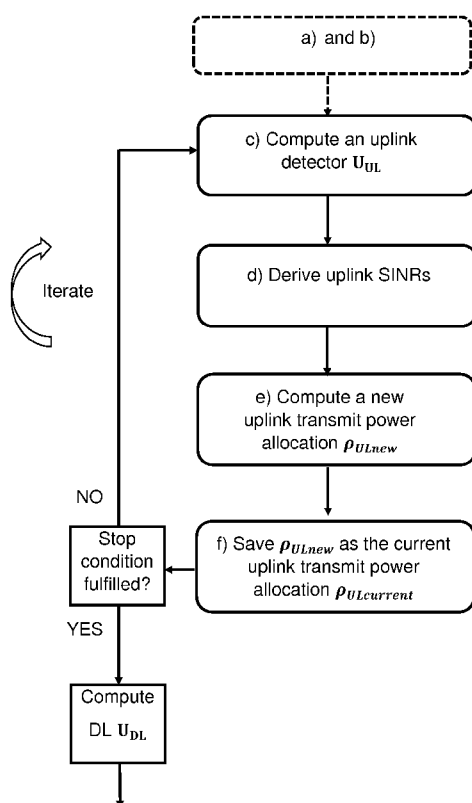


Fig. 3

(57) **Abstract:** The invention relates to a control device and a network node comprising such a control device (100). The control device (100) comprises a processor (102) configured to: a) obtain at least one pilot signal (410n) associated with a user device (400); b) compute an uplink channel estimation (G_{UL}) based on the at least one pilot signal (410n); c) compute an uplink detector (U_{UL}) based on the complex conjugate of the uplink channel estimation (G_{UL}) and a current uplink transmit power allocation ($P_{ULcurrent}$); d) derive uplink Signal-to-Interference and Noise Ratios, SINRs, based on the complex conjugate of the channel estimation (G_{UL}); e) compute a new uplink transmit power allocation (P_{ULnew}) by taking the ratio of the current uplink transmit power allocation ($P_{ULcurrent}$) to the uplink SINRs; compute a downlink precoder (U_{DL}) based on the uplink detector (U_{UL}). Furthermore, the invention also relates to corresponding methods, a wireless communication system, a computer program, and a computer program product.



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CONTROL DEVICE, NETWORK NODE AND METHODS THEREOF

TECHNICAL FIELD

The invention relates to a control device for a wireless communication system. Furthermore, the invention also relates to a network node comprising such a control device, corresponding methods, a wireless communication system, a computer program, and a computer program product.

BACKGROUND

For multi-cell systems, such as 3GPP Long Term Evolution (LTE), inter-cell interference is a significant impairment to downlink (DL) system performance. Conventional single-cell downlink massive multiple-input multiple-output (MIMO) systems which employ lower complexity linear precoders do not take into account inter-cell interference. Examples of such linear precoders are Beamforming, Transmit Matched Filter, Zero-Forcing, and Regularized Zero-Forcing precoders.

In DL massive MIMO transmission, interference aware precoding controls both the intra-cell interference and leakage of signals to other cells (i.e. inter-cell interference) such that an unprecedented system performance can be obtained. However, the determination of the precoders at the base stations according to a corresponding cost function turns out to be very difficult.

Conventional solutions for the design of the precoding matrices assume a given user power allocation. Thus, the user power allocations have to be determined. In most known massive MIMO downlink transmission schemes, the user power allocations are determined according to a maximum sum of user data rates. However, numerical results indicate that for such power allocations, the rates of different users are highly unbalanced, and very low user rates will result for certain users with poor channel conditions such as users at the cell edge.

SUMMARY

An objective of embodiments of the invention is to provide a solution which mitigates or solves the drawbacks and problems of conventional solutions.

Further objectives of embodiments of the invention include:

- Reduce downlink interference and noise experienced by user terminals with the

objective of minimizing the intra-cell and inter-cell interference and noise for user terminals in a sub-network via the design of downlink precoding matrices applied at respective base stations.

- Maximize the minimum user rate in the sub-network with the objective of maximizing the minimum user rate via downlink transmit power allocation to users in the sub-network, subject to per user transmit power constraints and also to specific sum power constraint.
- Provide an iterative algorithm which jointly solves the above two objectives.

10 The above objectives and further objectives are achieved by the subject matter of the independent claims. Further advantageous implementation forms of the invention are defined by the dependent claims.

15 According to a first aspect of the invention, the above mentioned and other objectives are achieved with a control device for a wireless communication system, the control device comprising a processor configured to:

- a) obtain at least one pilot signal associated with a user device;
- b) compute an uplink channel estimation based on the at least one pilot signal;
- c) compute an uplink detector based on the complex conjugate of the uplink channel estimation and a current uplink transmit power allocation;
- d) derive uplink Signal-to-Interference-and-Noise Ratios, SINRs, based on the complex conjugate of the channel estimation;
- e) compute a new uplink transmit power allocation by taking the ratio of the current uplink transmit power allocation to the uplink SINRs;
- 25 compute a downlink precoder based on the uplink detector.

The control device according to the first aspect provides a number of advantages over conventional control devices. One such advantage is that the minimum user data rate is much higher than for a maximum sum rate design, such that also cell-edge users can be served well.

30 Furthermore, all users enjoy the same data rates, i.e., the user data rates of the system are fully balanced.

In a first possible implementation form of a control device according to the first aspect, the processor is configured to:

f) save the new uplink transmit power allocation as the current uplink transmit power allocation;

g) repeat c) to f) at least one iteration.

- 5 The first possible implementation form provides an iterative approach of computing the downlink precoder. By repeating steps c) to f) the computed downlink precoder can be improved.

10 In a second possible implementation form of a control device according to the first implementation form of the first aspect, the processor is configured to terminate the iterations if the new uplink transmit power allocation computed in two subsequent iterations differ less than a threshold value.

The second implementation form provides a mechanism for stopping the iterations in order to avoid unnecessary computations which do not result in any further performance improvement.

- 15 In a third possible implementation form of a control device according to the first or second implementation form of the first aspect or to the first aspect as such, the processor, in the first iteration, is configured to compute the uplink detector based on a predetermined uplink transmit power allocation.

- 20 The third implementation form provides thus a way to initialize the iterative process.

25 In a fourth possible implementation form of a control device according to any of the first to the third implementation forms of the first aspect or to the first aspect as such, the processor is configured to derive the uplink SINRs by computing the uplink SINRs based on the uplink channel estimation, the uplink transmit power allocation and the uplink detector.

The fourth implementation form provides thus a way to determine the information for computing a new uplink transmit power allocation.

- 30 In a fifth possible implementation form of a control device according to any of the first to the third implementation forms of the first aspect or to the first aspect as such, the processor is configured to obtain the uplink SINRs by receiving measured downlink SINRs.

The fifth implementation form provides thus a way to avoid computing the uplink SINRs in order to save computational complexity.

5 In a sixth possible implementation form of a control device according to any of the preceding implementation forms of the first aspect or to the first aspect as such, the processor is configured to compute the downlink precoder by Hermitian transposition of the uplink detector.

The sixth implementation form provides a downlink precoder with high performance.

10 In a seventh possible implementation form of a control device according to any of the preceding implementation forms of the first aspect or to the first aspect as such, the processor is configured to compute a channel estimation error covariance based on statistics of the uplink channel, and compute the uplink detector further based on the channel estimation error covariance.

15 The seventh implementation form provides a precoder with a good robustness to channel estimation errors.

20 In an eighth possible implementation form of a control device according to any of the preceding implementation forms of the first aspect or to the first aspect as such, the processor is configured to compute a downlink transmit power allocation based on the new uplink transmit power allocation.

The eighth implementation form provides an optimized downlink transmit power allocation, which is of crucial importance for a high system performance in addition to the precoder.

25 In a ninth possible implementation form of a control device according to the eighth implementation form of the first aspect or to the first aspect as such, the processor is configured to precode data symbols addressed for the user device using the downlink precoder.

30 The ninth implementation form provides a component of a realization of a transmission with the abovementioned advantages.

According to a second aspect of the invention, the above mentioned and other objectives are achieved with a network node for a wireless communication system, the network node comprising

a control device according to any of preceding implementation forms of a control device according to the first aspect or to the first aspect as such, and

a transceiver configured to

receive the at least one pilot signal associated with the user device.

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In a first possible implementation form of a network node according to the first aspect, the transceiver is configured to

transmit the precoded data symbols to the user device according to the downlink transmit power allocation and the downlink precoder.

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According to a third aspect of the invention, the above mentioned and other objectives are achieved with a method comprising:

obtaining at least one pilot signal associated with a user device;

computing an uplink channel estimation based on the at least one pilot signal;

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computing an uplink detector based on the complex conjugate of the uplink channel estimation and a current uplink transmit power allocation;

deriving uplink Signal-to-Interference-and-Noise Ratios, SINRs, based on the complex conjugate of the channel estimation;

computing a new uplink transmit power allocation by taking the ratio of the current uplink

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transmit power allocation to the uplink SINRs;

computing a downlink precoder based on the uplink detector.

In a first possible implementation form of a method according to the third aspect, the method comprises:

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f) saving the new uplink transmit power allocation as the current uplink transmit power allocation;

g) repeating c) to f) at least one iteration.

In a second possible implementation form of a method according to the first implementation form of the third aspect, the method comprises

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terminating the iterations if the new uplink transmit power allocation computed in two subsequent iterations differ less than a threshold value.

In a third possible implementation form of a method according to the first or second implementation form of the third aspect or to the third aspect as such, the method comprises, in the first iteration,

computing the uplink detector based on a predetermined uplink transmit power allocation.

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In a fourth possible implementation form of a method according to any of the first to the third implementation forms of the third aspect or to the third aspect as such, the method comprises

deriving the uplink SINRs by computing the uplink SINRs based on the uplink channel estimation, the uplink transmit power allocation and the uplink detector.

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In a fifth possible implementation form of a method according to any of the first to the third implementation forms of the third aspect or to the third aspect as such, the method comprises

obtaining the uplink SINRs by receiving measured downlink SINRs.

15 In a sixth possible implementation form of a method according to any of the preceding implementation forms of the third aspect or to the third aspect as such, the method comprises

computing the downlink precoder by Hermitian transposition of the uplink detector.

20 In a seventh possible implementation form of a method according to any of the preceding implementation forms of the third aspect or to the third aspect as such, the method comprises

computing a channel estimation error covariance based on statistics of the uplink channel, and computing the uplink detector further based on the channel estimation error covariance.

25 In an eighth possible implementation form of a method according to any of the preceding implementation forms of the third aspect or to the third aspect as such, the method comprises

computing a downlink transmit power allocation based on the new uplink transmit power allocation.

30 In a ninth possible implementation form of a method according to the eighth implementation form of the third aspect or to the third aspect as such, the method comprises

precoding data symbols addressed for the user device using the downlink precoder.

In a tenth possible implementation form of a method according to the ninth implementation form of the third aspect, the method comprises

transmitting the precoded data symbols to the user device according to the downlink transmit power allocation.

5 In an eleventh possible implementation form of a method according to any of the preceding implementation forms of the third aspect or to the third aspect as such, the method comprises receiving the at least one pilot signal associated with the user device.

10 The advantages of the methods according to the third aspect are the same as for the corresponding control device according to the first aspect or to the network node according to the second aspect.

Embodiments of the invention also relate to a computer program, characterized in code means, which when run by processing means causes said processing means to execute any method according to the invention. Further, the invention also relates to a computer program product 15 comprising a computer readable medium and said mentioned computer program, wherein said computer program is included in the computer readable medium, and comprises of one or more from the group: ROM (Read-Only Memory), PROM (Programmable ROM), EPROM (Erasable PROM), Flash memory, EEPROM (Electrically EPROM) and hard disk drive.

20 Further applications and advantages of the invention will be apparent from the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

25 The appended drawings are intended to clarify and explain different embodiments of the invention, in which:

- Fig. 1 shows a control device according to an embodiment of the invention;
- Fig. 2 shows a corresponding method according to an embodiment of the invention;
- Fig. 3 shows an iterative approach according to an embodiment of the invention;
- Fig. 4 shows an exemplary implementation according to an embodiment of the invention 30 in which the control device is arranged in a network node;
- Fig. 5 shows a centralized solution according to an embodiment of the invention;
- Fig. 6 shows semi-centralized solution according to an embodiment of the invention;
- Fig. 7 shows signalling aspects of the embodiment in Fig. 6; and
- Figs. 8 and 9 show performance results.

DETAILED DESCRIPTION

Fig. 1 shows a control device 100 according to an embodiment of the invention. Further, Fig. 2 shows a corresponding method 200 which may be executed in a control device 100, such as the one shown in Fig. 1. The control device 100 may be a standalone device or being part of another radio network device. For example, the control device 100 may be an integrated part of a network node or of a central network node, such as a radio network controller. The present control device 100 at least comprises a processor 102 configured for processing. The processor 102 may be communicably coupled to optional transceiver 104, memory 106, etc. as illustrated in Fig. 1 with dashed lines. Also the processor 102 of the control device 100 may be shared with another network device, such as a network node, or may be a dedicated processor for executing the present algorithm only.

The processor 102 of the control device 100 is configured to: a) obtain at least one pilot signal 410 associated with a user device 400; and b) compute an UL channel estimation $\mathbf{G}_{UL}$ based on the at least one pilot signal 410. The pilot signal 410 may e.g. be obtained from the memory 106 or received from the transceiver 104 as illustrated in Fig. 1. The processor 102 of the control device 100 is further configured to:

- c) compute an UL detector $\mathbf{U}_{UL}$ based on the complex conjugate of the UL channel estimation $\mathbf{G}_{UL}$ and a current UL transmit power allocation $\rho_{ULcurrent}$. The received noise power distribution can also be used for computing the UL detector $\mathbf{U}_{UL}$;
- d) derive UL SINRs based on the complex conjugate of the channel estimation $\mathbf{G}_{UL}$;
- e) compute a new UL transmit power allocation ρ_{ULnew} by taking the ratio of the current uplink transmit power allocation $\rho_{ULcurrent}$ to the UL SINRs; and finally
- Compute a DL precoder $\mathbf{U}_{DL}$ based on the UL detector $\mathbf{U}_{UL}$.

The UL channel estimation may be based on a received UL signal comprising at least one pilot signal 410.

The UL SINRs may according to an embodiment be derived based on the complex conjugate of the channel estimation $\mathbf{G}_{UL}$ and the UL detector $\mathbf{U}_{UL}$.

The corresponding method 200, shown in the flow chart of Fig. 2, comprises:

- Obtaining 202 at least one pilot signal 400n associated with a user device 400;
- Computing 204 an UL channel estimation $\mathbf{G}_{UL}$ based on the at least one pilot signal 400;

- Computing 206 an UL detector $\mathbf{U}_{UL}$ based on the complex conjugate of the UL channel estimation $\mathbf{G}_{UL}$ and a current UL transmit power allocation $\rho_{ULcurrent}$;
- Deriving 208 UL SINRs based on the complex conjugate of the channel estimation $\mathbf{G}_{UL}$ and the UL detector $\mathbf{U}_{UL}$;
- 5 • Computing 210 a new UL transmit power allocation ρ_{ULnew} by taking the ratio of the current UL transmit power allocation $\rho_{ULcurrent}$ to the UL SINRs;
- Computing 212 a DL precoder $\mathbf{U}_{DL}$ based on the UL detector $\mathbf{U}_{UL}$.

10 It is to be noted that DL precoder $\mathbf{U}_{DL}$ may be computed for a plurality of user devices and not limited to a single user device. In that case pilot signals associated with a plurality of user devices are obtained. Each pilot signal is however associated with one user device only.

Further, the channel estimation is performed in the UL system to give estimates of the DL channel which equals the transpose of the UL channel in a Time Division Duplex (TDD) system. In a TDD
15 system, the DL channel is equal to the transpose of the UL channel. This is a physical property which can be shown via electromagnetic wave propagation experiments. The UL pilot signals are used to estimate the UL channel since this is needed for solving the DL precoder which assumes that the DL channel is known or an estimate of the DL channel is provided.

20 In an embodiment, an iterative approach is applied so as to provide improved DL precoder $\mathbf{U}_{DL}$. The iterative approach is illustrated in Fig. 3. Accordingly, the processor 102 of the control device 100 is according to this embodiment further configured to:

- f) save the new UL transmit power allocation ρ_{ULnew} as the current UL transmit power allocation $\rho_{ULcurrent}$. This step is for updating the UL transmit power allocation in the
25 iteration loop. The transmit power allocation can be saved in the memory 106; and
- Repeat the previous steps c) to f) at least one iteration.

Steps a) and b) described above are illustrated with dashed lines in Fig. 3.

30 In general, the present iterative loop can be seen to include an inner loop and an outer loop. In the outer loop, the equivalent UL detector $\mathbf{U}_{UL}$ is updated according to a sum MSE minimization for a given power allocation. In the inner loop, the power allocation for the user device is updated for given equivalent UL detector $\mathbf{U}_{UL}$ according to a procedure similar to that in for general

wireless networks. Here, only the SINRs of the current iteration and a prescribed maximum tolerable user power is necessary for the transmit power allocation update.

It is further noted that a stop criterion could be used so as to stop the iteration loop. In one embodiment the processor 102 is therefore configured to terminate the iterations if the new UL transmit power allocation ρ_{ULnew} computed in two subsequent iterations differ less than a threshold value. By doing so, unnecessary computations which do not result in any further noticeable performance improvement can be saved.

Mentioned threshold value should be chosen so as to balance the quality of the DL precoder $\mathbf{U}_{DL}$ condition on the number of iterations which determines the number of computations needed. If this stop condition is not fulfilled, i.e. NO in Fig. 3, the iteration loop continues meaning that steps c) to f) are repeated. However, if the stop condition is fulfilled, i.e. YES in Fig. 3, the DL precoder $\mathbf{U}_{DL}$ is computed based on uplink detector $\mathbf{U}_{UL}$ from the final iteration step.

Furthermore, in one embodiment the processor 102, in the very first iteration step, is configured to compute the UL detector $\mathbf{U}_{UL}$ based on a predetermined UL transmit power allocation ρ_{ULpre} . Hence, start values are inputted in the iteration loop. These values are needed to initialize the iterative process.

Moreover, the channel estimates derived from the pilot signals and the corresponding received UL signals can be used to compute the SINRs used in the present iteration. Alternatively, the SINRs can be measured. The SINRs are used for updating the UL power allocation in a dual UL system which is a mathematical model for solving the original DL power allocation problem. Once the optimal dual UL power allocation is found it is transformed back to the true DL power allocation.

Accordingly, in one embodiment the processor 102 is configured to derive the UL SINRs by computing the UL SINRs based on the UL channel estimation $\mathbf{G}_{UL}$, the UL transmit power allocation ρ_{UL} and the UL detector $\mathbf{U}_{UL}$.

In another embodiment the processor 102 of the control device 100 is configured to obtain the UL SINRs by receiving measured DL SINRs from the user device 400.

In one further embodiment, the processor 102 of the control device 100 is configured to compute the DL precoder $\mathbf{U}_{DL}$ by Hermitian transposition of the UL detector $\mathbf{U}_{UL}$. The Hermitian transpose of the (normalized) detector $\mathbf{U}_{UL}$ (unit norm rows) in the dual UL system gives the DL precoding matrix in the DL system.

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In yet another embodiment, the processor 102 of the control device 100 is configured to compute a channel estimation error covariance based on the statistics of the UL channel, and compute the UL detector $\mathbf{U}_{UL}$ further based on the channel estimation error covariance.

10 In yet one embodiment the DL precoder and DL transmit power allocation are jointly determined. Therefore, the processor 102 of the control device 100 is according to this embodiment configured to compute a DL transmit power allocation ρ_{DL} based on the new UL transmit power allocation ρ_{ULnew} . When computing the DL transmit power allocation ρ_{DL} system information, such as channel state information, optimized precoder, and noise power can further be used.

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For actual transmission to the user device 400 the data symbols addressed for user device 400 have to be precoded. Therefore, the processor 102 of the control device is configured to precode data symbols addressed for the user device 400 using the DL precoder $\mathbf{U}_{DL}$. Alternatively, the DL precoder and DL power allocation can be sent to a network node for DL precoding and DL transmit
20 power allocation at that network node.

Normally, the DL precoder and the DL transmit power allocation problems are very difficult to solve. For the multi-cell aware DL precoding problem, the precoders for all user devices in the cells in a cellular system need to be designed jointly which is a very complex optimization problem.
25 The complexity is even higher for the joint optimization of the DL precoding and power allocation problem.

The inventors have shown that the solution for the DL precoder matrices can be obtained via an equivalent sum mean-squared error (sum-MSE) minimizing UL detector design problem which is
30 easier to solve. Rather than solving the DL problem directly, the UL/DL duality for multi-cell multi-user MIMO systems can be applied according to Theorem 1 given in Appendix A, Section I-A. Theorem 1 is an extension of the single cell case to the multi-cell case. A dual multi-cell multi-user MIMO system UL system model to the DL system model can be used to solve the precoding and power allocation problems. For the dual UL/DL system models, the same per-user SINRs

and per-user MSEs can be achieved in the dual UL and DL systems, when the transmit powers are chosen appropriately.

The power allocation in the DL system can be obtained from the SINRs of the dual UL system, the channel estimation, UL detector, and UL power allocation.

For a fairer distribution of user data rates, a power allocation corresponding to a maximization of the minimum of all user data rates is considered in an embodiment. In this case, the equivalent UL detector vectors and user power allocations can be determined jointly.

For fixed equivalent UL detector vectors, the problem of determining the DL transmit power allocation becomes convex and can be solved in principle with interior point methods from convex optimization. However, the computational complexity becomes very high for practical problem sizes. To circumvent the above mentioned difficulty of high complexity in jointly determining the DL precoder and DL power allocation, efficient iterative algorithm for a close-to-optimum user power calculation has been considered.

Fig. 4 illustrates the case when the control device 100 is part of a network node 300 which comprises a transceiver 302. It is further illustrated how a user device transmits pilots 410 to the network node 300. By using the received pilot signals the control device 100 estimates the UL channel between the user device 400 and the network node 300. Fig. 4 also shows how the network node 300 transmits precoded data symbols 310 to the user device 400 according to the computed DL precoder and DL transmit power allocation ρ_{DL} .

Regarding different implementation aspects of the present solution, the control device 100 may be part of a fully centralized network solution, a fully distributed network solution or to a combination thereof. Moreover, also cooperative aspects between different network nodes of a wireless communication system 500 are considered in this disclosure. Hence, these aspects are illustrated in Figs. 5 to 7 in cellular or non-cellular settings.

Fig. 5 shows the embodiment in which the control device 100 is configured to act as a central control node, i.e. the fully centralized solution. The control device 100 is communicably connected via a wired and/or wireless backhaul 502 to a plurality of network nodes 300a, 300b,..., 300n configured to act as access nodes in the radio network of the wireless communication system

500. It is illustrated how a plurality of user devices 400a, 400b,..., 400n are transmitting pilots in the UL to their respective network nodes 300a, 300b,..., 300n. The network nodes 300a, 300b,..., 300n receive the pilots and forward the pilots to the control device 100.

5 The control device 100 computes in a centralized fashion the DL precoders and DL transmit power allocations for all the user devices 400a, 400b,..., 400n in the system 500. The DL precoders and DL transmit power allocations are thereafter signalled to the network nodes 300a, 300b,..., 300n which transmit data to the user devices 400a, 400b,..., 400n according to the DL precoders and DL transmit power allocations signalled from the control device 100.

10 Fig. 6 shows the embodiment in which each network node 300a, 300b,..., 300n comprises a control device. Fig. 7 illustrates signalling aspects of the exemplary embodiment in Fig. 6. The wireless communication system 500 in Fig. 6 may be a cellular system, such as LTE, comprising a plurality of subnetworks cooperating with each other. Network node 300a is configured to act
 15 as a coordination network node in the system 500. Each network node 300a, 300b,..., 300n may serve a cell or a sub-cell of the system 500. It is illustrated how the user devices 400a, 400b,..., 400n transmits pilot signals in the UL. Network node 300a receives UL pilot signals directly from user devices in its service area. With reference to Fig. 7 the following major signalling relating to information exchange for the present algorithm is performed in the wireless communication
 20 system 500:

- I: the control device 100 receives UL power allocation updates from network node 300b and 300n, respectively;
- A: the control device 100 aggregates the received power allocation updates from network node 300b and 300n;
- 25 • II: the control device 100 relays the received power allocation update information to the different network nodes, i.e. network node 300b and 300n in this example. Thereby, the received power allocation information is exchanged in the system;
- B: network nodes 300b and 300n check if the UL power allocations converge;
- III: the control device 100 receives requests from network node 300b and 300n to compute
 30 DL power allocation for each network node if the UL power allocations converge at B;
- IV: the control device 100 transmits the computed DL power allocation to network node 300b and 300n;
- C: network node 300b and 300n computes its respective DL precoder based on the received computed DL power allocation.

The control device 100 computes the DL transmit power allocation for the sub-network according to equations (6) and (7) below. T-BS obtains its DL transmit power allocation from the control device 100 and applies the transmit precoder and power allocations to the DL data to be transmitted according to the first term of equation (1) below. The control device 100 provides support in determining the DL power allocation and distributing power allocation and scheduling information to other network nodes in the sub-network.

For an even deeper understanding of the present solution a general theoretical framework is presented in the following disclosure. The aforementioned theoretical framework also gives examples of exemplary implementation embodiments. Therefore, system assumptions, system models, mathematical models, mathematical assumptions, etc. are presented and described. It should however be noted that the present solution is not limited to the mentioned system assumptions, system models, mathematical models, mathematical assumptions, etc., and only limited to the subject matter of the appended independent claims.

A multi-cell aware (MCA) precoder with sum rate maximizing and minimum rate maximizing power allocation schemes for downlink multi-cell massive multiple-input multiple-output (MIMO) systems is proposed. The proposed precoder herein exploits knowledge of the channel statistics but data exchange between different base stations (BSs, which fully correspond to “network nodes”) over backhaul links is not required. A correlated channel model is considered and the adopted channel state information (CSI) acquisition model includes the effects of estimation errors and pilot contamination. In contrast to the conventional regularized zero-forcing (RZF) precoder, which mitigates only the multi-user interference in the target cell, the proposed detector takes the interference from neighboring cells and pilot contamination into account and therefore achieves substantially higher performance. Moreover, in order to reduce the computational complexity, the matrix inversion required for the MCA precoder is approximated by a matrix polynomial leading to a new polynomial-expansion MCA (PEMCA) precoder. Using results from random matrix theory, we derive closed-form expressions for the optimal coefficients of the matrix polynomial, which only depend on the channel statistics but not on the channel realizations.

Furthermore, we propose sum rate maximizing and minimum rate maximizing (max-min) power allocation schemes for multi-cell massive MIMO systems. Our simulation results show that the proposed sum rate maximizing power allocation scheme performs better than the equal power allocation scheme, when the number of BS antennas is not much larger than the number of user

terminals (UTs, which fully correspond to user devices). However, in scenarios, where the number of BS antennas is much larger than the number of UTs, the sum rate maximizing power allocation achieves almost the same sum rate performance as the equal power allocation. On the other hand, the proposed max-min power allocation performs substantially better than the equal power allocation in the entire range of BS antennas.

We consider the downlink of a time division duplex (TDD) operated multi-cell massive MIMO system with universal frequency reuse. The number of cells is denoted by L , and in each cell, K single-antenna UTs simultaneously receive data from a BS equipped with K antennas. K and N are assumed to be very large with their ratio $\beta = K / N$ being constant. The independent and identically distributed (i.i.d.) zero-mean complex Gaussian data symbols intended to be transmitted to the UTs in the l th cell are stacked into the vector $\mathbf{d}_l = [d_{l1}, \dots, d_{lK}]^T$, $E\{\mathbf{d}_l \mathbf{d}_l^H\} = \mathbf{I}_K$ where $\mathbf{d}_{lk}$ is the data symbol of the k th UT in the l th cell. The stacked vector of the received signals at the UTs in the j th cell is given by

$$\hat{\mathbf{d}}_j = \mathbf{G}_{jj}^H \mathbf{V}_j \mathbf{P}_j^{1/2} \mathbf{d}_j + \sum_{l=1, l \neq j}^L \mathbf{G}_{lj}^H \mathbf{V}_l \mathbf{P}_l^{1/2} \mathbf{d}_l + \mathbf{w}_j \quad (1)$$

where $\mathbf{G}_{lj} = [\mathbf{g}_{lj1} \dots \mathbf{g}_{ljK}] \in \mathbb{C}^{N \times K}$ with $\mathbf{g}_{lj}$ being the channel vector between k th UT in the j th cell and the l th BS. Here, $\mathbf{P}_j = \text{diag}(P_{j1}, \dots, P_{jK})$ denotes the power allocation matrix of the UTs in the j th cell with P_{jk} being the transmit power of the k th UT. Moreover, $\mathbf{w}_j \sim \text{CN}(\mathbf{0}, \mathbf{I}_K)$ represents the stacked vector of the additive white Gaussian noise (AWGN) of the UTs in the j th cell. We assume a block fading channel. We further assume a correlated channel model, i.e., $\mathbf{g}_{ljk} = \tilde{\mathbf{R}}_{ljk} \mathbf{h}_{ljk}$, where $\mathbf{h}_{ljk} \sim \text{CN}(\mathbf{0}, \mathbf{I}_N)$, and $\mathbf{R}_{ljk} = E[\mathbf{g}_{ljk} \mathbf{g}_{ljk}^H] = \tilde{\mathbf{R}}_{ljk} \tilde{\mathbf{R}}_{ljk}^H$ represents the covariance matrix of the channel between the k th UT in the j th cell and the l th BS. We adopt a channel correlation model which comprises large-scale fading and antenna correlation, i.e., $\tilde{\mathbf{R}}_{ljk} = \sqrt{\alpha_{ljk}} \mathbf{A}$, where $\mathbf{A}$ models the BS antenna correlation and α_{ljk} denotes the large-scale fading factor. For α_{ljk} we consider two models. For the derivation of the coefficients of the polynomial – expansion precoder, we assume that α_{ljk} is equal to one for $j=1$ (direct gain), and η for $j \neq l$ (cross gain). For the power allocation derivation, we assume $\alpha_{ljk} = x_{ljk}^{-3.7}$, where x_{ljk} is the distance between the k th UT in the j th cell and the l th BS. Moreover, $\mathbf{V}_j = [\mathbf{v}_{j1} \dots \mathbf{v}_{jK}] \in \mathbb{C}^{N \times K}$ represents

the precoding matrix at the j th BS with $\mathbf{v}_{jk} \in \mathbb{C}^{N \times 1}$ being the precoder vector of the k th UT. Depending on the precoding strategy, the precoding matrix is calculated from the channel estimates of either the UTs in the target cell to the target BS for the conventional RZF precoder and the MCA precoder, respectively. The channel estimation is performed during the uplink transmission, where UTs transmit training sequences to their serving BS. However, due to the limited coherence time of the channel, it is not possible to make the channel estimation training sequences of all UTs in all cells mutually orthogonal. Hence, we assume that UTs with the same index in different cells use the same training sequences. This leads to a corrupted channel estimate and the related effect is known as pilot contamination in the massive MIMO literature. Considering this effect and assuming MMSE channel estimation, the estimated channel vector between the k th UT in the j th cell and the l th BS can be modeled as

$$\hat{\mathbf{g}}_{ljk} = \mathbf{\Omega}_{ljk} \left(\sum_{j'=1}^L \mathbf{g}_{lj'k} + \frac{1}{\sqrt{\rho_{TR}}} \mathbf{w}_{lk} \right), \quad (2)$$

where $\mathbf{\Omega}_{ljk}$ is defined as

$$\mathbf{\Omega}_{ljk} = \mathbf{R}_{ljk} \left(\sum_{j'=1}^L \mathbf{R}_{lj'k} + \frac{1}{\rho_{TR}} \mathbf{I}_N \right)^{-1} \quad (3)$$

with ρ_{TR} being the training SNR. Based on (1), the signal-to-interference-plus-noise ratio (SINR) for the k th UT in the j th cell is given by

$$\text{SINR} \triangleq \frac{p_{jk} \left| \mathbf{g}_{jjk}^H [\mathbf{v}_j]_{:,k} \right|^2}{\sum_{l=1}^L \sum_{\substack{k'=1 \\ (l,k') \neq (j,k)}}^K p_{lk'} \left| \mathbf{g}_{ljk}^H [\mathbf{v}_j]_{:,k'} \right|^2 + 1}, \quad (4)$$

In this section, we drive the multi-cell aware precoding. The optimization criterion we use is the minimization of the sum of the multi-user interference in the cell under consideration and induced interference in all other cells (leakage). The sum-MSE minimization problem for determining the precoder matrix $\mathbf{V}_j$ and the power allocation matrix in the j th cell can be formulated as follows:

$$\begin{aligned} \min_{\mathbf{V}_j, \mathbf{P}_j} & \mathbb{E} \left\{ \left\| \mathbf{G}_{jj}^H \mathbf{V}_j \mathbf{P}_j^{1/2} \mathbf{d}_j + \mathbf{w}_j - \mathbf{d}_j \right\|^2 + \sum_{l \neq j} \left\| \mathbf{G}_{jl}^H \mathbf{V}_j \mathbf{P}_j^{1/2} \mathbf{d}_j \right\|^2 \right\} \\ & \text{subject to: } \text{tr}(\mathbf{V}_j^H \mathbf{V}_j) = 1, \\ & \text{tr}(\mathbf{P}_j) = P_{TX}, \end{aligned} \quad (5)$$

where P_{TX} is the total transmit power of the UTs per cell and $\hat{\mathbf{G}}_j = [\hat{\mathbf{G}}_{j1} \ \cdots \ \hat{\mathbf{G}}_{jL}]$ with $\hat{\mathbf{G}}_{jl} = [\hat{\mathbf{g}}_{jl1} \cdots \hat{\mathbf{g}}_{jlK}]$.

The problem in (5) is not easy to solve due to the presence of both optimization variables, i.e., the precoding matrix $\mathbf{V}_j$ and the power allocation matrix $\mathbf{P}_j$ in the constraint. Hence, in the next section, we introduce the uplink/downlink duality theorem, where the downlink system model with the corresponding optimization problem is transformed to its dual uplink model with a simpler optimization problem. The obtained solution of the dual uplink optimization problem is then transformed back to the downlink solution.

In this section, we introduce the uplink/downlink duality for multi-cell multi-user MIMO systems. If the dual uplink system model, the precoding, detection, and power allocation matrices are defined properly, the same individual SINR in the downlink can be obtained as in the dual uplink model. This result is presented in the following theorem.

Theorem 1: Under the same sum power constraint, the same individual SINRs in the downlink and dual uplink systems can be achieved if the detector matrix $\mathbf{U}_j \in \mathbb{C}^{K \times N}$ has unit norm rows and the precoder matrix $\mathbf{V}_j$ is equal to the Hermitian of the detector matrix, i.e., $\mathbf{V}_j = \mathbf{U}_j^H$. The channel matrix in the dual uplink model is given by the Hermitian of the channel matrix in the downlink model. Moreover, the vectorized downlink power allocation $\tilde{\mathbf{p}} \in \mathbb{C}^{LK \times 1}$ is given by

$$\tilde{\mathbf{p}} = \text{vec}(\tilde{\mathbf{P}}) = (\mathbf{I}_{KL} - \text{diag}(\mathbf{b})\mathbf{B}^T)^{-1}\mathbf{b}, \quad (6)$$

where $\tilde{\mathbf{P}} \in \mathbb{C}^{L \times K}$ and $\left[\tilde{\mathbf{P}} \right]_{j,:} = (\text{diag}(\mathbf{P}_j))^T$ and the elements of the vector $\mathbf{b} \in \mathbb{C}^{KL}$ and the matrix

$\mathbf{B} \in \mathbb{C}^{KL \times KL}$ are defined as follows:

$$\begin{aligned} [\mathbf{b}]_k &= \frac{\text{SINR}_{jk}^{\text{UL}}}{(1 + \text{SINR}_{jk}^{\text{UL}}) \left| [\mathbf{U}_j]_{k,:} \mathbf{g}_{jjk} \right|^2}, \\ [\mathbf{B}]_{(j-1)K+k, (l-1)K+k'} &= \left| [\mathbf{U}_j]_{k,:} \mathbf{g}_{jlk'} \right|^2, \end{aligned} \quad (7)$$

where $k, k' \in \{1, \dots, K\}$.

Applying the uplink/downlink duality to the downlink optimization problem in (5), following dual uplink optimization problem is obtained

$$\min_{\mathbf{U}_j, \mathbf{Q}_j} \mathbb{E} \left\{ \left\| \mathbf{U}_j (\mathbf{G}_{jj} \mathbf{Q}_j^{1/2} \mathbf{d}_j + \mathbf{w}_j) - \mathbf{d}_j \right\|^2 + \sum_{l \neq j}^L \left\| \mathbf{U}_j \mathbf{G}_{jl} \mathbf{Q}_l^{1/2} \mathbf{d}_l \right\|^2 \middle| \hat{\mathbf{G}}_j \right\}, \quad (8)$$

where $\mathbf{Q}_j = \text{diag}(q_{j1}, \dots, q_{jK})$ is the power allocation matrix of the UTs in the j th cell in the dual uplink system with q_{jk} being the transmit power of the k th UT in the j th cell. Since obtaining closed-form matrix polynomial coefficients and optimizing the power allocation scheme is sophisticated, in this section we assume an equal power allocation. The solution to the optimization problem in (8) is given by the following theorem.

Theorem 2: In an uplink multi-cell massive MIMO system with pilot contamination, imperfect channel estimation, and equal power allocation, the following detector matrix minimizes the conditional expectation of the sum-MSE given the estimates of the channels between the BS in the target cell and the UTs in all cells

$$\mathbf{U}_j^{MCA} = \frac{1}{N} \hat{\mathbf{G}}_{jj}^H \left(\sum_{l=1}^L \frac{1}{N} (\hat{\mathbf{G}}_{jl} \hat{\mathbf{G}}_{jl}^H + \Delta_{jl}) + \frac{1}{N \rho_{UL}} \mathbf{I}_N \right)^{-1}. \quad (9)$$

where $\rho_{UL} = q_{jk}$, $\forall j \in \{1, \dots, L\}$, $k \in \{1, \dots, K\}$ is the UTs transmit power, and the channel estimation error covariance matrix Δ_{jl} is given by

$$\Delta_{jl} = \mathbb{E} \{ \tilde{\mathbf{G}}_{jl} \tilde{\mathbf{G}}_{jl}^H \mid \tilde{\mathbf{G}}_j \} = \sum_{k=1}^K (\mathbf{R}_{jlk} - \Phi_{jlk}), \quad (10)$$

where $\tilde{\mathbf{G}}_{jl} = \mathbf{G}_{jl} - \hat{\mathbf{G}}_{jl}$ and the channel estimation covariance matrix Φ_{jlk} is defined as

$$\Phi_{jlk} = \mathbb{E} \{ \hat{\mathbf{g}}_{jlk} \mathbf{g}_{jlk}^H \} = \mathbf{R}_{jlk} \left(\sum_{l'=1}^L \mathbf{R}_{jl'l'k} + \frac{1}{\rho_{TR}} \mathbf{I}_N \right)^{-1} \mathbf{R}_{jlk}. \quad (11)$$

As can be observed from (9), the MCA detection matrix is constructed from three components. The first component, $\hat{\mathbf{G}}_{jj}^H$, is the estimated channel matrix of the channels of the UTs in the target cell and is present in both the MCA and the MMSE detector

$$\mathbf{U}_j^{MMSE} = \frac{1}{N} \hat{\mathbf{G}}_{jj}^H \left(\frac{1}{N} (\hat{\mathbf{G}}_{jj} \hat{\mathbf{G}}_{jj}^H) + \frac{1}{N \rho_{UL}} \mathbf{I}_N \right)^{-1}.$$

The second component, $\sum_{l=1, l \neq j}^L \hat{\mathbf{G}}_{jl} \hat{\mathbf{G}}_{jl}^H$, is not present in the conventional MMSE detector and contains information regarding the estimated channel between the UTs in other cells and the considered BS, which is exploited by the MCA detector to suppress multi-cell interference. The third component in the MCA detection matrix is $\sum_{l=1}^L \Delta_{jl} = \sum_{l=1}^L \mathbb{E} \left\{ \hat{\mathbf{G}}_{jl} \hat{\mathbf{G}}_{jl}^H \middle| \hat{\mathbf{G}}_j \right\}$, where

5 $\tilde{\mathbf{G}}_{jl} = \mathbf{G}_{jl} - \hat{\mathbf{G}}_{jl}$ is the estimation error matrix of the channels between the UTs in the l th cell and the j th BS. This part accounts for the CSI imperfection caused by, e.g., pilot contamination. The MCA detector can also be used in a single-cell scenario with imperfect CSI which motivates the following corollary.

10 *Corollary 1:* In an uplink single-cell massive MIMO system with imperfect channel estimation, the following CSI aware (CSIA) detector minimizes the conditional expectation of the sum-MSE given the estimated channel matrix of the UTs in the target cell

$$\mathbf{U}_j^{\text{CSIA}} = \frac{1}{N} \hat{\mathbf{G}}_{jj}^H \left(\frac{1}{N} (\hat{\mathbf{G}}_{jj} \hat{\mathbf{G}}_{jj}^H) + \frac{1}{N} \Delta'_{jl} + \frac{1}{N_{\rho_{UL}}} \mathbf{I}_N \right)^{-1} \quad (12)$$

where the matrix Δ'_{jl} is defined as

$$15 \quad \Delta'_{jl} = \sum_{k=1}^K (\mathbf{R}_{jlk} - \Phi'_{jlk}), \quad (13)$$

with Φ'_{jlk} being given by

$$\Phi'_{jlk} = \mathbf{R}_{jlk} \left(\mathbf{R}_{jlk} + \frac{1}{\rho_{\text{TR}}} \mathbf{I}_N \right)^{-1} \mathbf{R}_{jlk}. \quad (14)$$

20 *Proof:* Substituting $L=1$ into (9), (10), and (11), and performing simple mathematical manipulations yields (12).

As can be seen in (12), in contrast to the MMSE detector, the CSIA detector takes into account the effect of the CSIA imperfection through the additional term Δ'_{jl} .

25 In this section, we derive sum rate maximizing and minimum rate maximizing power allocation schemes for the dual uplink system. As mentioned in the previous section, the derived power

allocation and detection matrices in the dual uplink system can be then transformed to their downlink counterparts by using uplink/downlink duality theorem.

The network-wide sum rate maximization problem in the uplink massive MIMO with unit norm detector vectors and individual transmit power constraint can be formulated as

$$\begin{aligned} \max_{\mathbf{u}_\kappa, q_\kappa} \sum_{\kappa=1}^{LK} \log_2 \left(1 + \frac{q_\kappa |\mathbf{u}_\kappa \mathbf{g}_\kappa|^2}{\sum_{\kappa'=1, \kappa' \neq \kappa}^{LK} q_{\kappa'} |\mathbf{u}_{\kappa'} \mathbf{g}_{\kappa'}|^2 + 1} \right) \\ \text{s.t. } 0 \leq q_\kappa \leq q_\kappa, \forall \kappa \in \{1, \dots, LK\} \end{aligned} \quad (15)$$

where we have introduced the new variable $\kappa = (l-1)K + k$, which is the index of the k th UT in the l th cell. Here, $\mathbf{u}_\kappa$, q_κ , and q_κ are the unit norm detection vector, the transmit power of the κ th UT, and the transmit power constraint of the κ th UT, respectively. The problem in (15) is in general non-convex. However, for large SINR, the objective function in (15) is equivalent to

$$\max_{\mathbf{u}_\kappa, q_\kappa} \prod_{\kappa=1}^{LK} \frac{q_\kappa |\mathbf{u}_\kappa \mathbf{g}_\kappa|^2}{\sum_{\kappa'=1, \kappa' \neq \kappa}^{LK} q_{\kappa'} |\mathbf{u}_{\kappa'} \mathbf{g}_{\kappa'}|^2 + 1} \quad (16)$$

which can be rewritten as

$$\min_{\mathbf{u}_\kappa, q_\kappa} \prod_{\kappa=1}^{LK} \sum_{\kappa'=1, \kappa' \neq \kappa}^{LK} \frac{q_{\kappa'} |\mathbf{u}_{\kappa'} \mathbf{g}_{\kappa'}|^2}{q_\kappa |\mathbf{u}_\kappa \mathbf{g}_\kappa|^2} + \frac{1}{q_\kappa |\mathbf{u}_\kappa \mathbf{g}_\kappa|^2} \quad (17)$$

Considering (17), the sum rate maximizing problem in (15) can be reformulated as

$$\begin{aligned} \min_{\mathbf{u}_\kappa, q_\kappa} \prod_{\kappa=1}^{LK} \sum_{\kappa'=1, \kappa' \neq \kappa}^{LK} q_{\kappa'} q_\kappa^{-1} |\mathbf{u}_{\kappa'} \mathbf{g}_{\kappa'}|^2 |\mathbf{u}_\kappa \mathbf{g}_\kappa|^{-2} + q_\kappa^{-1} |\mathbf{u}_\kappa \mathbf{g}_\kappa|^{-2} \\ \text{s.t. } 0 \leq q_\kappa \leq q_\kappa, \forall \kappa \in \{1, \dots, LK\} \end{aligned} \quad (18)$$

Nevertheless, the joint optimization of the detector vectors $\mathbf{u}_\kappa$ and transmit power q_κ in (18) is still challenging, since the optimal detector vectors depend on the transmit powers and vice versa, and to the best of our knowledge, there exist no solution in the open research library. One suitable technique for solving problems such as (18) is the so called alternate optimization, where first, one variable is optimized by assuming that the second variable is fixed and then the second

variable is optimized by using the first variable obtained in the previous step and performing iterations.

Now assuming fixed detector vectors $\mathbf{u}_\kappa$, the problem in (18) becomes a geometric programming (GP) problem, since the objective function is a product of sum of polynomials and can be represented as a polynomial too. In particular, for fixed detector vectors $\mathbf{u}_\kappa, \forall \kappa \in \{1, \dots, LK\}$, and after applying the variable transformation $y = \log x$, the optimization problem in (18) becomes convex and can be solved efficiently.

Here, in order to obtain the detection vectors for a given power allocation in the alternate optimization, the sum-MSE minimization is applied. Then the sum rate maximization problem for given detector vectors is solved to obtain the power allocation. The obtained power allocation is then used to update the detector vectors and the whole procedure is iterated. The sum-MSE minimization problem for fixed power allocations is given by

$$\min_{\mathbf{u}_j} E \left[\left\| \mathbf{u}_j \mathbf{G}_{jj} \mathbf{Q}_j^{1/2} \mathbf{d}_j + \mathbf{u}_j \mathbf{w}_j - \mathbf{d}_j \right\|^2 + \sum_{\substack{l=1 \\ l \neq j}}^L \left\| \mathbf{u}_j \mathbf{G}_{jl} \mathbf{Q}_l^{1/2} \mathbf{d}_l \right\|^2 \right] \widehat{\mathbf{G}}_j \quad (19)$$

Similar to Theorem 2, it can be shown that a detector matrix, whose k^{th} row is given by the following expression is the solution to the sum-MSE minimization problem in (19)

$$\mathbf{u}_{jk} = \widehat{\mathbf{g}}_{jjk}^H \left(\sum_{l=1}^L \sum_{k'=1}^K q_{lk'} \widehat{\mathbf{g}}_{jlk'} \widehat{\mathbf{g}}_{jlk'}^H + \sum_{l=1}^L \sum_{k'=1}^K q_{lk'} \Delta_{jlk'} + \mathbf{I}_N \right)^{-1} \quad (20)$$

where $q_{lk'}$ is the transmit power of the k' th UT in the l th cell and $\Delta_{jlk'} = \mathbf{R}_{jlk'} - \Phi_{jlk'}$ is the channel estimation error covariance matrix of the k' th UT in the l th cell to the j th BS. Now, the sum rate maximizing power allocation problem in (18) can be solved by assuming the detector vectors obtained from (20). An efficient and fast algorithm for solving the optimization problem in (18) has been proposed in C. W. Tan, M. Chiang, and R. Srikant, "Fast Algorithms and Performance Bounds for Sum Rate Maximization in Wireless Networks," *IEEE/ACM Trans. Networking*, vol. 21, no. 3, pp. 706–719, Jun. 2013. Using this algorithm, the sum rate maximizing transmit power of the κ th UT is obtained by the following fixed-point equation

$$q_\kappa^{(m+1)} = \min \left\{ \left(\sum_{\kappa'=1, \kappa' \neq \kappa}^{LK} \frac{[\mathbf{F}]_{\kappa', \kappa} SINR_{\kappa'}^{(m)}}{q_{\kappa'}^{(m)}} \right)^{-1}, \widetilde{q}_\kappa \right\} \quad (21)$$

where $\kappa = (l-1)K + k$ and (m) denotes the iteration index. The elements of the matrix $\mathbf{F} \in \mathbb{C}^{LK \times LK}$ are defined as follows:

$$[\mathbf{F}]_{\kappa, \kappa'} = \begin{cases} \frac{|\mathbf{u}_\kappa \mathbf{g}_{\kappa'}|^2}{|\mathbf{u}_\kappa \mathbf{g}_\kappa|^2}, & \text{if } \kappa \neq \kappa' \\ 0, & \text{otherwise} \end{cases} \quad (22)$$

Once the transmit powers are obtained by (21), the detector vectors can be calculated using (20). Then, after performing a few iterations the algorithm converges to the final solution.

10 In this section, the max-min power allocation scheme is introduced. The corresponding optimization problem is given by

$$\begin{aligned} \max_{\mathbf{u}_\kappa, q_\kappa} \min_{\kappa} \log_2 & \left(1 + \frac{q_\kappa |\mathbf{u}_\kappa \mathbf{g}_\kappa|^2}{\sum_{\kappa'=1, \kappa' \neq \kappa}^{LK} q_{\kappa'} |\mathbf{u}_\kappa \mathbf{g}_{\kappa'}|^2 + 1} \right) \\ \text{s.t. } & 0 \leq q_\kappa \leq \bar{q}_\kappa, \forall \kappa \in \{1, \dots, LK\} \end{aligned} \quad (23)$$

Similar to the sum rate maximizing problem in (15), jointly optimizing the detection vectors $\mathbf{u}_\kappa$ and transmit powers q_κ in (23) is very difficult. Thus, we apply the alternate optimization technique to solve the problem in (23). In particular, we propose a heuristic solution, where the detection vectors $\mathbf{u}_\kappa$ are obtained by solving the sum-MSE minimization problem in (19). Then, the max-min power allocation problem in (23) is solved for the obtained detection vectors. To solve the problem in (23) for given detector vectors $\mathbf{u}_\kappa$, we apply the efficient fixed-point algorithm introduced in the cited paper above, which has been proposed for general wireless networks

$$\begin{aligned} q_\kappa^{(m+1)} &= \frac{q_\kappa^{(m)}}{\text{SINR}_\kappa^{(m)}} \\ q_\kappa^{(m+1)} &= \frac{q_\kappa q_\kappa^{(m+1)}}{\max_{\kappa'} q_{\kappa'}^{(m+1)}} \end{aligned} \quad (24)$$

Note that m is the iteration index and the second step in (24) is performed to ensure the per user power constraint. We note that according to our observations, for both sum rate maximizing and max-min power allocation problems, the maximum UT powers are good initial values for the corresponding fixed-point equations.

Proof of theorem 2: Using the properties $E\{\mathbf{d}_j^H \mathbf{d}_l\} = 0, \forall j \neq l$, $E\{\mathbf{d}_j^H \mathbf{n}_l\} = 0, \forall j, l$, substituting $\mathbf{Q}_l = \mathbf{I}_K, \forall l \in \{1, \dots, L\}$, and performing simple mathematical manipulations, the optimization objective in (8) can be reformulated as

$$E_{G_{jl}} \left\{ \text{tr} \left(\rho_{UL} (\mathbf{U}_j \mathbf{G}_{jj} - \mathbf{I}_K) (\mathbf{G}_{jj}^H \mathbf{U}_j^H - \mathbf{I}_K) + \rho_{UL} \sum_{l=1, l \neq j}^L \mathbf{U}_j \mathbf{G}_{jl} \mathbf{G}_{jl}^H \mathbf{U}_j^H + \mathbf{U}_j \mathbf{U}_j^H \right) \middle| \hat{\mathbf{G}}_j \right\} = 0, \forall j \neq l \quad (25)$$

- 5 Now we consider $\mathbf{G}_{jl} = \hat{\mathbf{G}}_{jl} + \tilde{\mathbf{G}}_{jl}$, where $\tilde{\mathbf{G}}_{jl}$ is the estimation error matrix of the channels between the UTs in the l th cell and the j th BS, exploit the independence of $\hat{\mathbf{G}}_{jl}$ and $\tilde{\mathbf{G}}_{jl}$ for linear MMSE estimation, and obtain

$$E \left\{ \mathbf{G}_{jl} \mathbf{G}_{jl}^H \middle| \hat{\mathbf{G}}_j \right\} = \mathbf{G}_{jl} \mathbf{G}_{jl}^H + \Delta_{jl}, \quad (26)$$

where $\Delta_{jl} = E \left\{ \mathbf{G}_{jl} \mathbf{G}_{jl}^H \middle| \hat{\mathbf{G}}_j \right\}$ is given by

$$10 \quad \Delta_{jl} = \sum_{k=1}^K (\mathbf{g}_{jlk} \mathbf{g}_{jlk}^H - \hat{\mathbf{g}}_{jlk} \hat{\mathbf{g}}_{jlk}^H) = \sum_{k=1}^K (\mathbf{R}_{jlk} - \Phi_{jlk}) \quad (27)$$

with $\Phi_{jlk} = E \left\{ \hat{\mathbf{g}}_{jlk} \hat{\mathbf{g}}_{jlk}^H \right\}$ being the channel estimation matrix given in (11). Substituting (26) into (25), we obtain

$$\text{tr} \left(\rho_{UL} \mathbf{U}_j \left(\sum_{l=1}^L \hat{\mathbf{G}}_{jl} \hat{\mathbf{G}}_{jl}^H + \Delta_{jl} \right) \mathbf{U}_j^H - \rho_{UL} \mathbf{U}_j \hat{\mathbf{G}}_{jj} - \rho_{UL} \hat{\mathbf{G}}_{jj}^H \mathbf{U}_j^H + \mathbf{U}_j \mathbf{U}_j^H \right) + \rho_{UL} K. \quad (28)$$

- 15 Now, in order to derive $\mathbf{U}_j^{\text{MCA}}$, we take the derivative of the optimization objective function in (28) and set it to zero

$$\frac{\partial}{\partial \mathbf{U}_j^*} E_{\mathbf{d}_j, \mathbf{n}_j, \mathbf{G}_{jl}} \left\{ \|\mathbf{d}_j - \hat{\mathbf{d}}_j\|^2 \middle| \hat{\mathbf{G}}_j \right\} = \rho_{UL} \mathbf{U}_j \left(\sum_{l=1}^L \hat{\mathbf{G}}_{jl} \hat{\mathbf{G}}_{jl}^H + \Delta_{jl} \right) - \rho_{UL} \hat{\mathbf{G}}_{jj}^H + \mathbf{U}_j = 0 \quad (29)$$

- 20 Performing simple algebraic operations, $\mathbf{U}_j^{\text{MCA}}$ as given in (9) is obtained. Note that we included the normalization factor $1/N$ in the expression in (9), which does not change the result but facilitates the later derivation of the asymptotic optimal coefficients in the large system limit. This completes the proof.

The present solution permits a wireless communication system 500 to achieve the highest minimum rate for all users in the network compared with other schemes, while at the same time achieving a sum rate for the radio network which is better than for conventional single-cell schemes for Massive MIMO systems where the number of antenna elements in an antenna array can be of size $N = 64$, or $N = 128$. These effects are shown by the results in Fig. 8 and Fig. 9 in which Fig. 8 shows the network-wide sum rate vs. N for $L = 7$ (number of cells), $K = 20$ (number of users per cell), $\rho_{DL} = 20 \text{ dB}$, and $\rho_{TR} = 20 \text{ dB}$ (SNR for downlink transmission and channel estimation, respectively); and Fig. 9 shows the network-wide min rate vs N for $L = 7$, $K = 20$, $\rho_{DL} = 20 \text{ dB}$, and $\rho_{TR} = 20 \text{ dB}$. The x-axis shows the number of antennas N and the y-axis the minimum rate in bits/s/Hz in Figs. 8 and 9.

It should be noted that the user data rates of the wireless communication system 500 are balanced with the present solution. All users enjoy the same data rate and cell edge users can be served well. Further, as mentioned above for an example system, consider 7 cells with 20 users per cell and a base station with 50 antennas. Under realistic signal-to-noise ratios, the proposed design is able to improve the minimum user data rate by 200% compared to a maximum sum rate design.

A user device 400 may e.g. be any of a User Terminal (UT), a User Equipment (UE), mobile station (MS), wireless terminal or mobile terminal which is enabled to communicate wirelessly in a wireless communication system, sometimes also referred to as a cellular radio system. The UE may further be referred to as mobile telephones, cellular telephones, computer tablets or laptops with wireless capability. The UEs in the present context may be, for example, portable, pocket-storable, hand-held, computer-comprised, or vehicle-mounted mobile devices, enabled to communicate voice or data, via the radio access network, with another entity, such as another receiver or a server. The UE can be a Station (STA), which is any device that contains an IEEE 802.11-conformant Media Access Control (MAC) and Physical Layer (PHY) interface to the Wireless Medium (WM).

A (radio) network node 300 or an access node or an access point or a Base Station (BS), e.g., a Radio Base Station (RBS), which in some networks may be referred to as transmitter, "eNB", "eNodeB", "NodeB" or "B node", depending on the technology and terminology used. The radio network nodes may be of different classes such as, e.g., macro eNodeB, home eNodeB or pico base station, based on transmission power and thereby also cell size. The radio network node can be a Station (STA), which is any device that contains an IEEE 802.11-conformant Media

Access Control (MAC) and Physical Layer (PHY) interface to the Wireless Medium (WM).

Furthermore, any methods according to embodiments of the invention may be implemented in a computer program, having code means, which when run by processing means causes the processing means to execute the steps of the method. The computer program is included in a computer readable medium of a computer program product. The computer readable medium may comprises of essentially any memory, such as a ROM (Read-Only Memory), a PROM (Programmable Read-Only Memory), an EPROM (Erasable PROM), a Flash memory, an EEPROM (Electrically Erasable PROM), or a hard disk drive.

Moreover, it is realized by the skilled person that the control device 100 comprises the necessary communication capabilities in the form of e.g., functions, means, units, elements, etc., for performing the present solution. Examples of other such means, units, elements and functions are: processors, memory, buffers, control logic, encoders, decoders, rate matchers, de-rate matchers, mapping units, multipliers, decision units, selecting units, switches, interleavers, de-interleavers, modulators, demodulators, inputs, outputs, antennas, amplifiers, receiver units, transmitter units, DSPs, MSDs, TCM encoder, TCM decoder, power supply units, power feeders, communication interfaces, communication protocols, etc. which are suitably arranged together for performing the present solution.

Especially, the processors of the present control device 100 may comprise, e.g., one or more instances of a Central Processing Unit (CPU), a processing unit, a processing circuit, a processor, an Application Specific Integrated Circuit (ASIC), a microprocessor, or other processing logic that may interpret and execute instructions. The expression "processor" may thus represent a processing circuitry comprising a plurality of processing circuits, such as, e.g., any, some or all of the ones mentioned above. The processing circuitry may further perform data processing functions for inputting, outputting, and processing of data comprising data buffering and device control functions, such as call processing control, user interface control, or the like.

Finally, it should be understood that the invention is not limited to the embodiments described above, but also relates to and incorporates all embodiments within the scope of the appended independent claims.

CLAIMS

1. Control device for a wireless communication system (500), the control device (100) comprising a processor (102) configured to:
 - 5 a) obtain at least one pilot signal (410n) associated with a user device (400);
 - b) compute an uplink channel estimation ($\mathbf{G}_{UL}$) based on the at least one pilot signal (410n);
 - c) compute an uplink detector ($\mathbf{U}_{UL}$) based on the complex conjugate of the uplink channel estimation ($\mathbf{G}_{UL}$) and a current uplink transmit power allocation ($\rho_{ULcurrent}$);
 - d) derive uplink Signal-to-Interference and Noise Ratios, SINRs, based on the complex
 - 10 conjugate of the channel estimation ($\mathbf{G}_{UL}$);
 - e) compute a new uplink transmit power allocation (ρ_{ULnew}) by taking the ratio of the current uplink transmit power allocation ($\rho_{ULcurrent}$) to the uplink SINRs;
 - compute a downlink precoder ($\mathbf{U}_{DL}$) based on the uplink detector ($\mathbf{U}_{UL}$).
- 15 2. Control device (100) according to claim 1, wherein the processor (102) is configured to:
 - f) save the new uplink transmit power allocation (ρ_{ULnew}) as the current uplink transmit power allocation ($\rho_{ULcurrent}$);
 - g) repeat c) to f) at least one iteration.
- 20 3. Control device (100) according to claim 2, wherein the processor (102) is configured to terminate the iterations if the new uplink transmit power allocation (ρ_{ULnew}) computed in two subsequent iterations differ less than a threshold value.
4. Control device (100) according to any of claims 1 to 3, wherein the processor (102), in the first
- 25 iteration, is configured to compute the uplink detector ($\mathbf{U}_{UL}$) based on a predetermined uplink transmit power allocation (ρ_{ULpre}).
5. Control device (100) according to any of claims 1 to 4, wherein the processor (102) is configured to derive the uplink SINRs by computing the uplink SINRs based on the uplink channel estimation
- 30 ($\mathbf{G}_{UL}$), the uplink transmit power allocation (ρ_{UL}) and the uplink detector ($\mathbf{U}_{UL}$).
6. Control device (100) according to any of claims 1 to 4, wherein the processor (102) is configured to obtain the uplink SINRs by receiving measured downlink SINRs.

7. Control device (100) according to any of the preceding claims, wherein the processor (102) is configured to compute the downlink precoder ($\mathbf{U}_{DL}$) by Hermitian transpose of the uplink detector ($\mathbf{U}_{UL}$).

8. Control device (100) according to any of the preceding claims, wherein the processor (102) is configured to compute a channel estimation error covariance based on statistics of the uplink channel, and compute the uplink detector ($\mathbf{U}_{UL}$) further based on the channel estimation error covariance.

9. Control device (100) according to any of the preceding claims, wherein the processor (102) is configured to compute a downlink transmit power allocation (ρ_{DL}) based on the new uplink transmit power allocation (ρ_{ULnew}).

10. Control device (100) according to claim 9, wherein the processor (102) is configured to precode data symbols addressed for the user device (300) using the downlink precoder ($\mathbf{U}_{DL}$).

11. Network node (300) for a wireless communication system (500), the network node (300) comprising:

a control device (100) according to any of claims 1 to 10; and

a transceiver (302) configured to receive the at least one pilot signal associated with the user device (400).

12. Network node (300) according to claim 11 when dependent on claim 10, wherein the transceiver (302) is configured to:

transmit the precoded data symbols (310) to the user device (400) according to the downlink transmit power allocation (ρ_{DL}).

13. Method for a control device (100), the method (200) comprising:

obtaining (202) at least one pilot signal (400n) associated with a user device (400);

computing (204) an uplink channel estimation ($\mathbf{G}_{UL}$) based on the at least one pilot signal (400);

computing (206) an uplink detector ($\mathbf{U}_{UL}$) based on the complex conjugate of the uplink channel estimation ($\mathbf{G}_{UL}$) and a current uplink transmit power allocation ($\rho_{ULcurrent}$);

- deriving (208) uplink Signal-to-Interference and Noise Ratios, SINRs, based on the complex conjugate of the channel estimation ($\mathbf{G}_{UL}$);
- computing (210) a new uplink transmit power allocation (ρ_{ULnew}) by taking the ratio of the current uplink transmit power allocation ($\rho_{ULcurrent}$) to the uplink SINRs;
- 5 computing (212) a downlink precoder ($\mathbf{U}_{DL}$) based on the uplink detector ($\mathbf{U}_{UL}$).

14. Computer program with a program code for performing a method according to claim 13 when the computer program runs on a computer.

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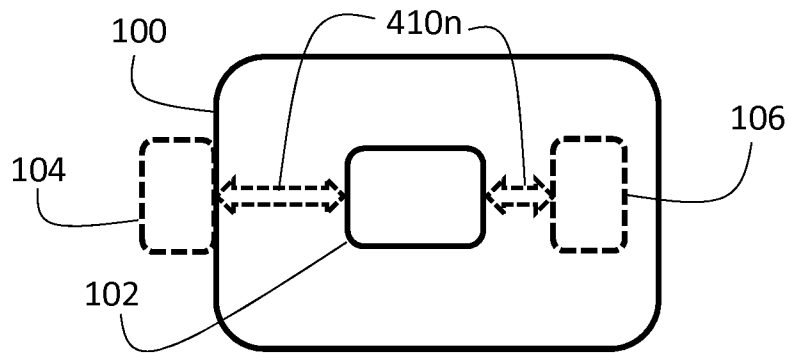


Fig. 1

200 →

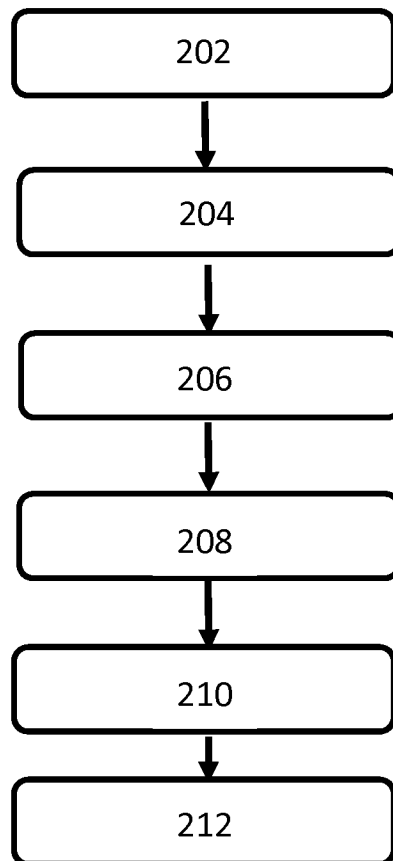


Fig. 2

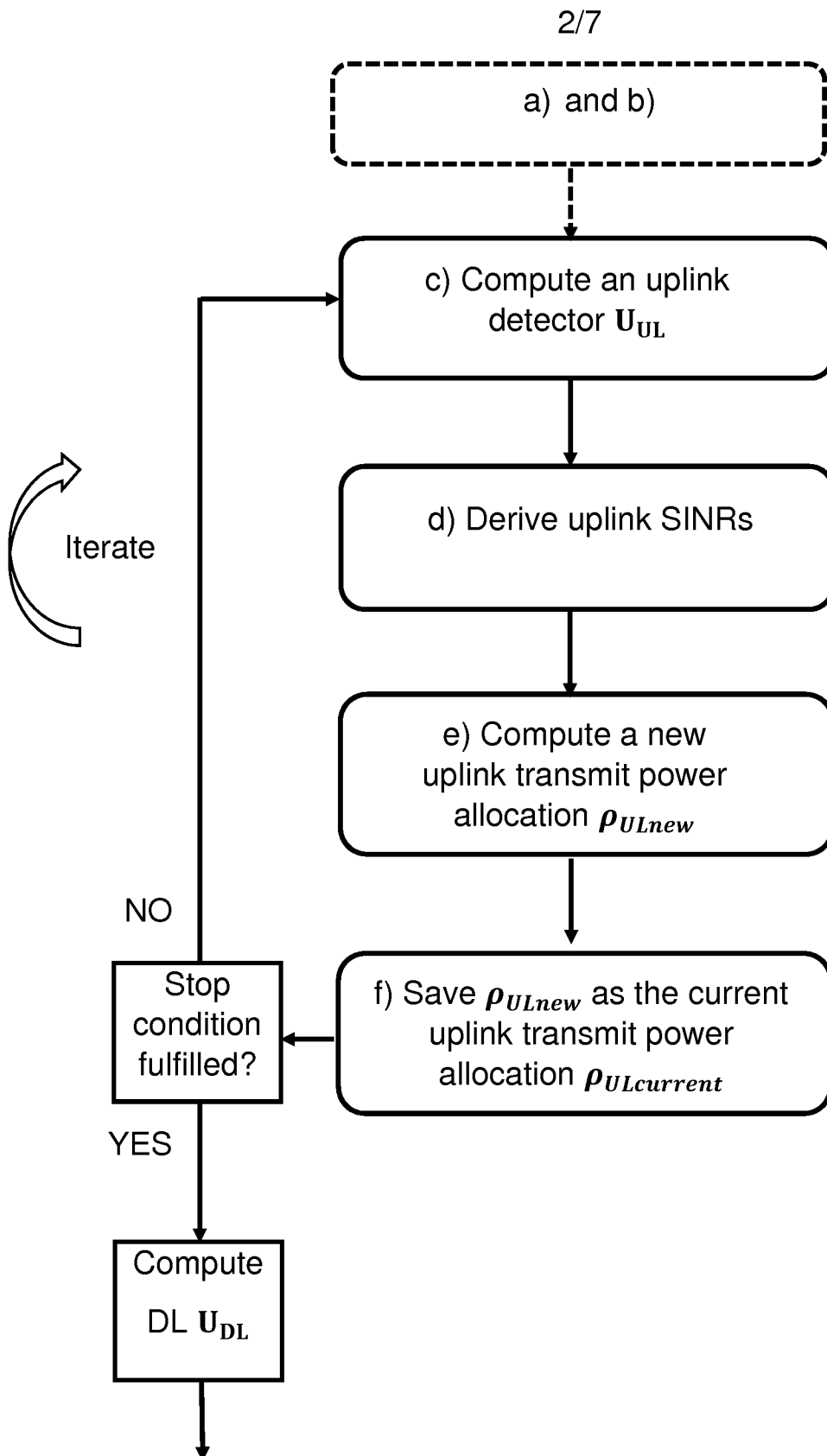


Fig. 3

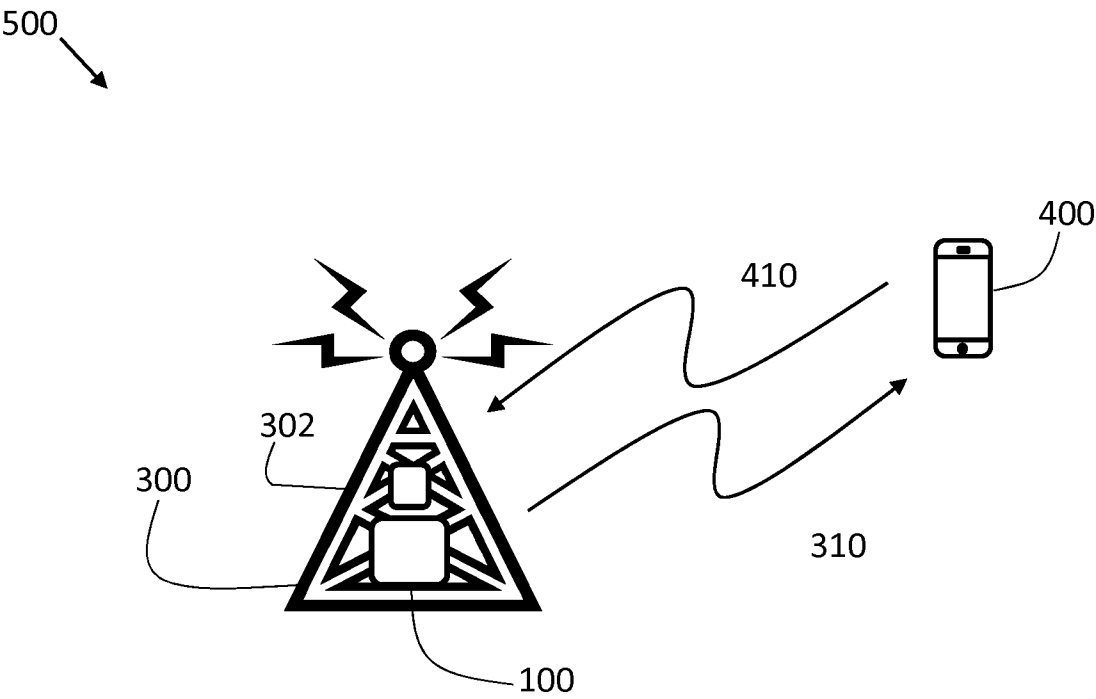


Fig. 4

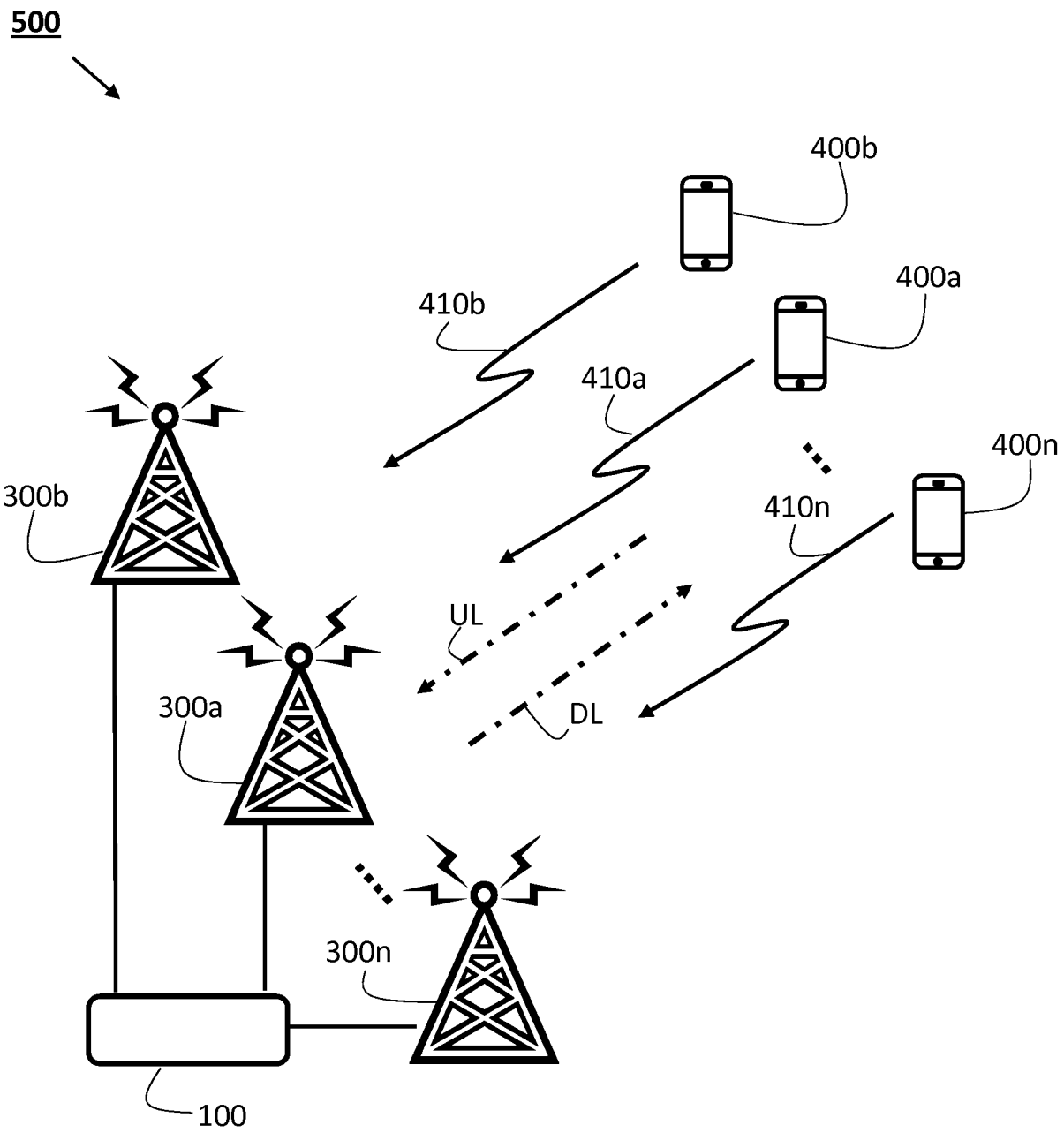


Fig. 5

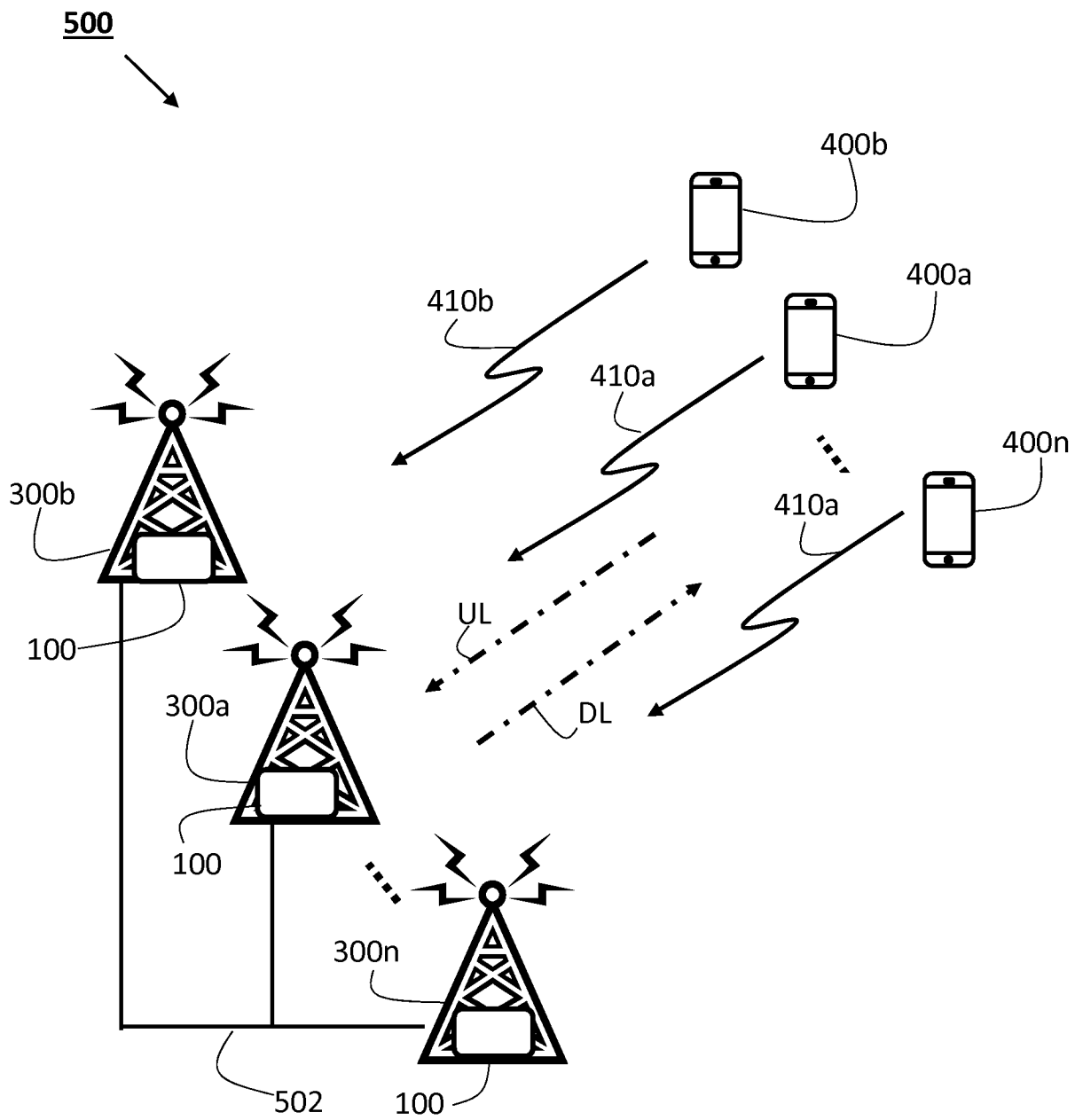


Fig. 6

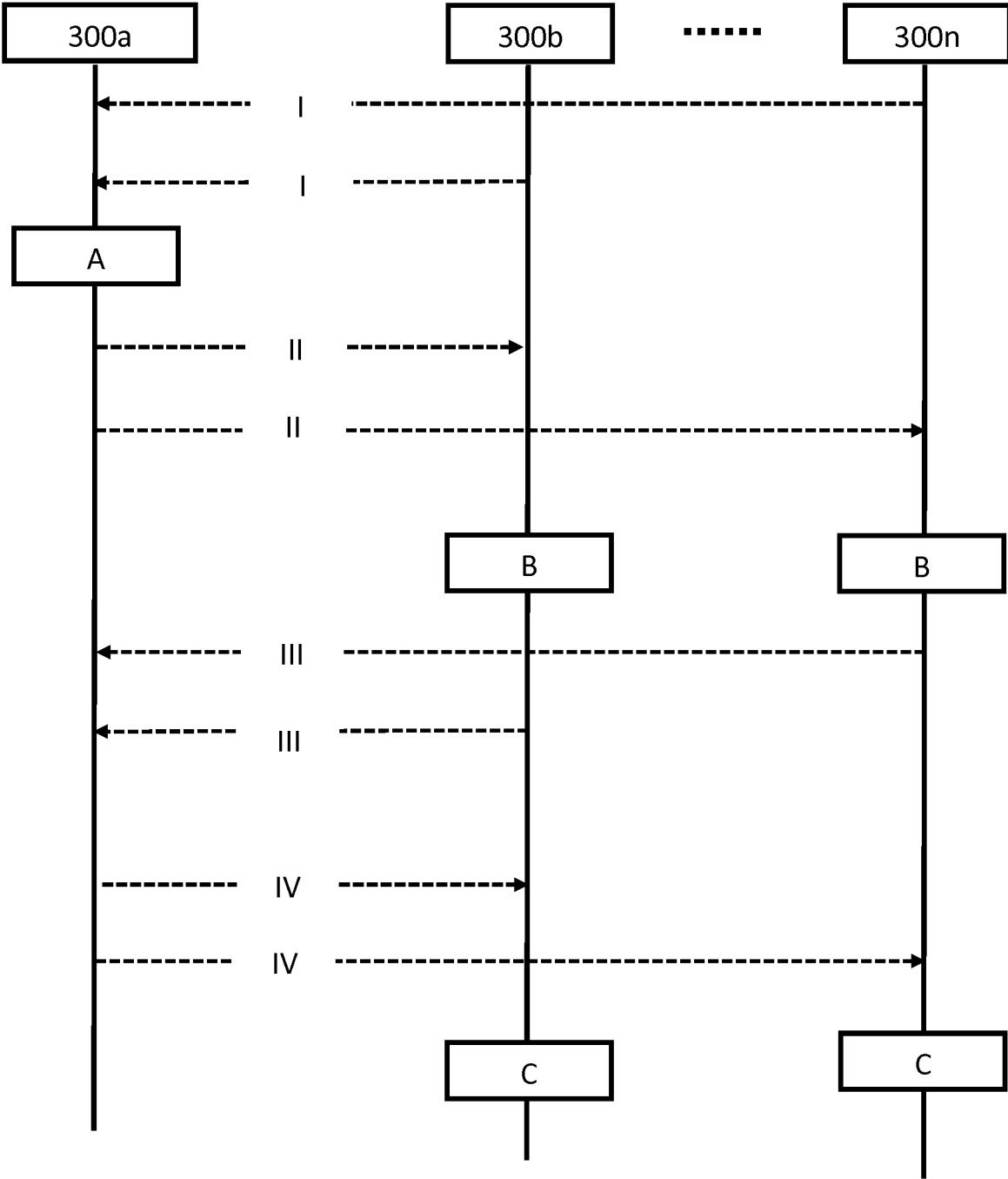


Fig. 7

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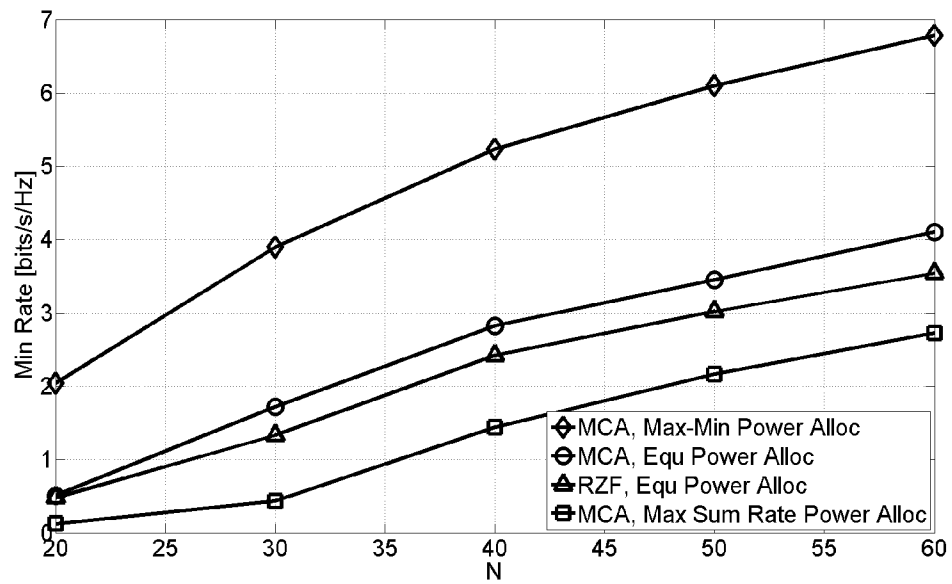


Fig. 8

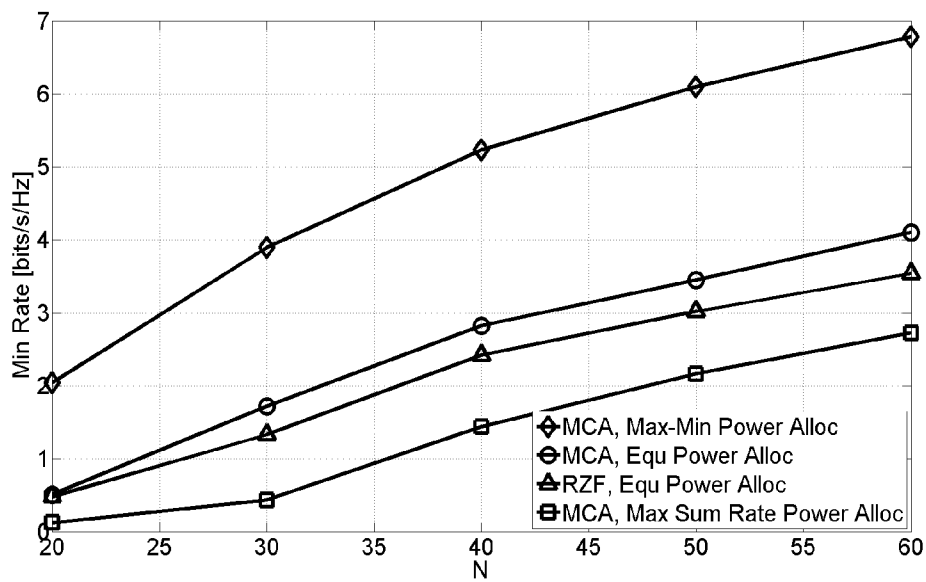


Fig. 9

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/058456

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04W52/14 H04W52/24 H04B7/06
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04W H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	BJORNSON EMIL ET AL: "Optimal Design of Energy-Efficient Multi-User MIMO Systems: Is Massive MIMO the Answer?", IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 14, no. 6, 1 June 2015 (2015-06-01), pages 3059-3075, XP011584060, ISSN: 1536-1276, DOI: 10.1109/TWC.2015.2400437 [retrieved on 2015-06-08] page 3060 - page 3062; figures 1,2 page 3064 - right-hand column, last paragraph page 3073 - right-hand column, last paragraph ----- -/-	1-14



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

1 December 2016

Date of mailing of the international search report

12/12/2016

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Authorized officer

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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/058456

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	CHEE WEI TAN ET AL: "Fast Algorithms and Performance Bounds for Sum Rate Maximization in Wireless Networks", IEEE / ACM TRANSACTIONS ON NETWORKING, IEEE / ACM, NEW YORK, NY, US, vol. 21, no. 3, 1 June 2013 (2013-06-01), pages 706-719, XP011514821, ISSN: 1063-6692, DOI: 10.1109/TNET.2012.2210240 Section III.C; page 710 -----	1-14
A	ZAREI SHAHRAM ET AL: "Polynomial-Expansion Multi-Cell Aware Detector for Uplink Massive MIMO Systems with Imperfect CSI", 2015 IEEE GLOBAL COMMUNICATIONS CONFERENCE (GLOBECOM), IEEE, 6 December 2015 (2015-12-06), pages 1-6, XP032872134, DOI: 10.1109/GLOCOM.2014.7416964 [retrieved on 2016-02-23] the whole document -----	1-14