A Downlink Transmission Method for MIMO Systems with Whitening Filters to Reduce Interference from both Inner and Outer Cells

Manabu MIKAMI[1,2] and Teruya FUJII[1,2]
[1] Information and Communications Laboratries, Japan Telecom Co., LTD.
38 Aomi 2-Chome, Koutou-ku, Tokyo, 135–8070 Japan.
E-mail : {manabu.mikami,teruya.fujii}@japan-telecom.co.jp
[2] R&D Center, BB Mobile Corp.
1–9–1 Higashi-Shimbashi, Minato-ku, Tokyo, 105–7304 Japan.
E-mail : {ma-mikami,te-fujii}@bb.softbank.co.jp

***Abstract*—MIMO (Multiple-Input Multiple-Output) transmission technologies with multiple antennas at both transmitter and receiver are attracting attention for realizing ultra high bit rate data transmission in wireless communications. Unfortunately, the MIMO performance in multi-user radio access systems can be degraded due to the interference from inner and outer cells. In this paper, we propose a novel MIMO transmission method for the downlink of mobile radio access systems in multi-cell/multi-user environments. The proposed method uses whitening filters at both the transmitter and the receiver to reduce the interference from inner and outer cells, respectively. We evaluate the performance of the proposed transmission method.**

Keywords; Multi-user MIMO system, Multi-cell environments, Whitening filter, Inner and outer cell interference reduction

I. INTRODUCTION

MIMO (Multiple-Input Multiple-Output) transmission technologies offer ultra high-speed data transmission with multiple antennas at both the transmitter and the receiver in wireless communication systems and have attached much attention because they can increase system capacity within the same frequency bandwidth. Researches on MIMO transmission have mostly assumed single-cell/single-user environments. However, multi-user MIMO systems (in which multiple users communicate with a radio base station at the same frequency and the same timing) are being considered in order to introduce MIMO transmission technologies to multi-user radio access systems. Such systems, however, will suffer from MAI (Multiple Access Interference). Because the MAI degrades the performance of MIMO transmission, several methods that can reduce the co-channel interference are proposed for the uplink and the downlink of multi-user radio access systems [1]-[4]. The downlink in particular requires higher transmission capacity than the uplink because the main application at the downlink is web browsing or file downloading. Therefore, it is more important to develop MIMO transmission methods for the downlink than the uplink. Previous works on downlink transmission methods for multi-user MIMO systems consider only inner-cell interference as the inter-user interference. However, the outer-cell interference is also a significant problem in multi-cell environments. This paper proposes a novel MIMO transmission method for the downlink of mobile radio access systems in multi-cell/multi-user environments. The proposed transmission method uses whitening filters [3] at both the transmitter and the receiver to reduce the interference from inner and outer cells, respectively. We evaluate the performance of the proposed transmission method.

II. PROPOSED MULTI-CELL/MULTI-USER MIMO SYSTEMS

A. System model

As shown in Figure 1, the proposed system places a spatial filter at each transmitter (Base station) to reduce the inner-cell interference $\boldsymbol{W}_{t,ij}$, and a spatial filter at each receiver (Mobile station) to reduce the outer-cell interference $\boldsymbol{W}_{r,ij}^{H}$. Here, the superscript H denotes matrix conjugate transpose. The proposed system is designed for multi-user MIMO systems in

---

A portion of this work is sponsored by the Strategic Information and Communications R&D Promotion Program (SCOPE) of the Ministry of Internal Affairs and Communications of Japan.

multi-cell environments. By the way, there are various MIMO transmission methods [5] such as V-BLAST [6], STBC-MIMO [7], Space Division Multiplexing with MLD [8] (where the MIMO channel state information (CSI) is not used at the transceiver), MIMO eigenmode transmission (where the CSI is used at the transceiver) [9], [10] and so on. In this paper, we apply the MIMO eigenmode transmission method as MIMO multi-stream transmission method. As shown in Figure 1, in this paper, the CSI matrix $\boldsymbol{H}_{ij}$ is defined as the matrix consisting of the CSI from the transmit antennas at the base station (BS) in the *i*-th cell, BS #*i*, to the receive antennas at the *j*-th mobile station in the *i*-th cell, MS #(*i*, *j*). The number of MSs per cell is J, the number of transmit antennas of each BS is N_t, and the number of receive antennas of each MS is N_r. On the other hand, CSI matrix $\boldsymbol{G}_{k,ij}$ is defined as the matrix consisting of the CSI from the transmit antennas at the BS in the *k*-th cell, BS #*k*, to the receive antennas at MS #(*i*, *j*). The data transmitted to each MS $\boldsymbol{s}_{ij}(t)$ is multiplied at the BS #*i* by both the antenna weight matrix $\boldsymbol{V}_{ij}$ for MIMO eigenmode transmission and the spatial filter matrix $\boldsymbol{W}_{t,ij}$ for reducing MAI from the inner cell. Moreover, the transmitted data vector of each MS $\boldsymbol{s}_{ij}(t)$ is also multiplied by scaling factor α_{ij} in order to hold the average transmitted power constant, because the norm of the weight matrix combined $\boldsymbol{W}_{t,ij}$ and $\boldsymbol{V}_{ij}$, $\left\|\boldsymbol{W}_{t,ij}\boldsymbol{V}_{ij}\right\|$, is not always a unit quantity (=1). On the other hand, the signal vector received at each antenna of each MS $\boldsymbol{x}_{ij}(t)$ is multiplied by both the spatial filter matrix $\boldsymbol{W}_{r,ij}^{H}$ to reduce multi-cell interference and antenna weight matrix $\boldsymbol{U}_{ij}^{H}$ for separating and detecting the multiple streams sent to each MS.

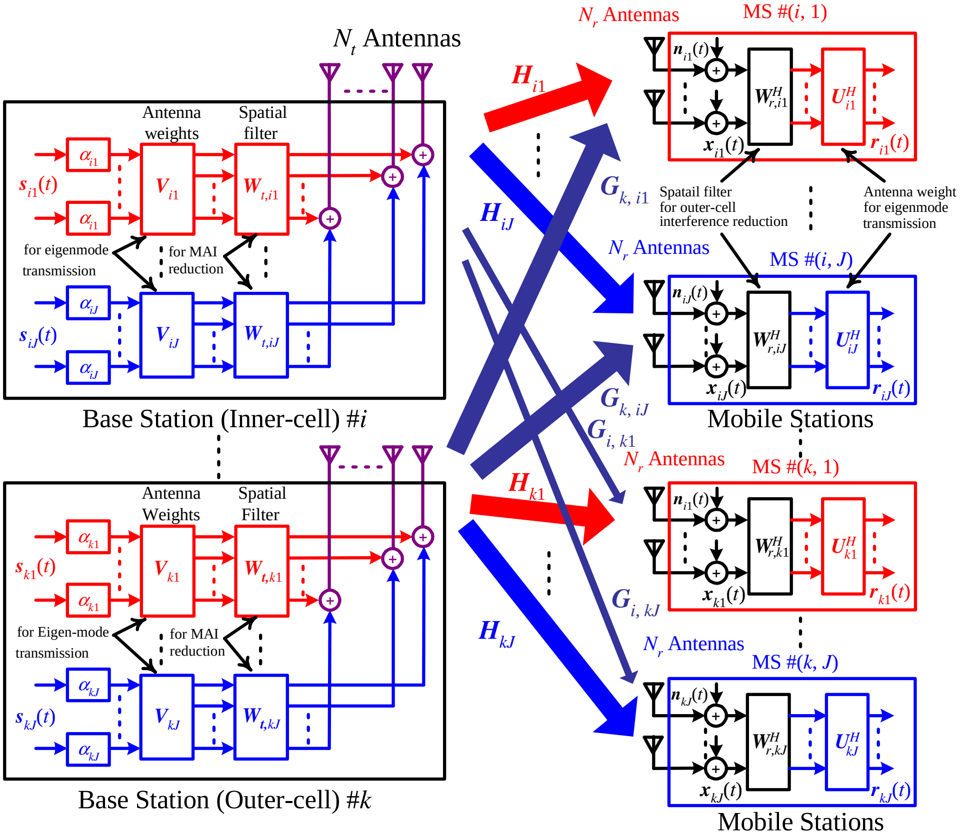


Figure 1. System model

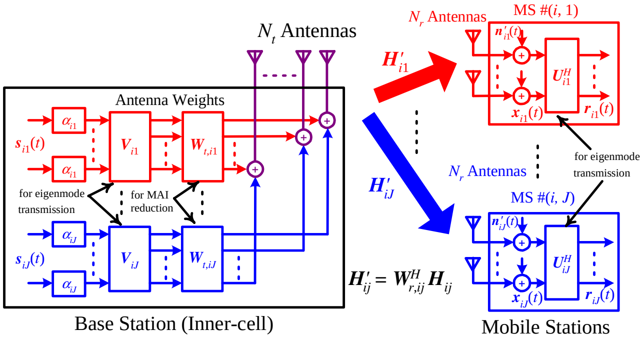


Figure 2. Equivalent single-cell/multi-user MIMO transmission model without outer-cell interference by using whitening filter at the receiver ($i = 1,\ldots,K$).

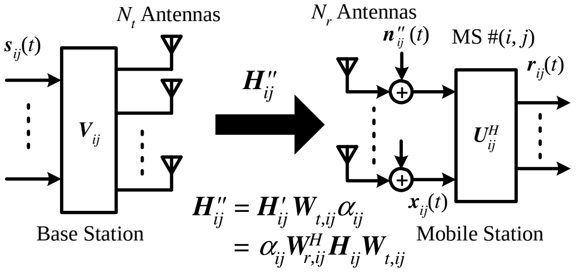


Figure 3. Equivalent single-cell/single-user MIMO transmission model without inner-cell and outer-cell interference by using whitening filters at the receiver and the transmitter $(i = 1,\ldots,K,\ j = 1,\ldots,J)$.

B. *Basic concept of proposed model*

Our proposal uses whitening filters as the spatial filters $W_{t,ij}$, $W^H_{r,ij}$ in order to reduce the inner-cell and outer-cell interference at the downlink of mobile radio access systems. The whitening filters transform the interference and the receiver thermal noises into white Gaussian noises in the following three steps.

(1) Each MS estimates the receiver spatial correlation matrix $R^{(r)}_{uu,ij}$ of the outer-cell interference including the thermal noise at the receiver and calculates the whitening filter coefficients $W^H_{r,ij}$ from the correlation matrix $R^{(r)}_{uu,ij}$ in order to reduce the outer-cell interference (see appendix in detail). The whitening filter at the receiver of each MS, $W^H_{r,ij}$, transforms the outer-cell interference into uncorrelated Gaussian noise. This means that the multi-cell/multi-user MIMO system shown in Figure 1 can be transformed into several parallel independent equivalent single-cell/multi-user MIMO systems without outer-cell interference shown in Figure 2.

(2) Each MS feeds back the CSI matrix including the whitening filter coefficients at the downlink, $H'_{ij} = W^H_{r,ij} H_{ij}$, to the BS. Accordingly, each BS can obtain the CSI matrices of all MSs H'_{ij} in the inner cell.

(3) From the obtained CSI matrices H'_{ij} , each BS estimates the transmitter spatial correlation matrices of the inter-cell interference, $R^{(t)}_{uu,ij}$, for all MSs in the inner cell, and calculates the whitening filter coefficients at the transmitter $W_{t,ij}$ for the all MSs in order to reduce the inner-cell interference (see appendix in detail). The whitening filter at the transceiver of each BS, $W_{t,ij}$, also transforms the inner-cell interference into uncorrelated Gaussian noise. This means that the equivalent multi-user MIMO system shown in Figure 2 can be transformed into several parallel, independent, equivalent single-user MIMO systems with the MIMO channel of each user $H''_{ij} = \alpha_{ij} W^H_{r,ij} H_{ij} W_{t,ij}$ shown in Figure 3 (Hereafter, H''_{ij} is called the “equivalent MIMO channel matrix”). Therefore, the multi-cell/multi-user MIMO system shown in Figure 1 is equivalent to the single-cell/single-user MIMO system shown in Figure 3. By using the equivalent model, we can easily assess various MIMO transmission methods for multi-cell/multi-user MIMO systems.

C. *MIMO eigenmode transmission*

As described in the above section, we apply MIMO eigenmode transmission [9], [10], which can maximize the MIMO channel capacity; the multi-stream transmission method is one example. In MIMO eigenmode transmission, transmitter weight of each user, V_{ij} , and receiver weight of each user, U^H_{ij} , can be derived by Singular Value Decomposition (SVD) of the equivalent MIMO channel matrix, H''_{ij} . The equivalent MIMO channel matrix, H''_{ij} , is also expressed as $H''_{ij} = U_{ij} \Sigma_{ij} V^H_{ij}$, where Σ_{ij} is the diagonal matrix composed by the non-zero singular values of H''_{ij} , U_{ij} and V_{ij} are the left and right singular matrices of H''_{ij} , respectively.

TABLE I. SIMULATION PARAMETERS

Number of BSs	$K = 2$
Number of MSs per cell	$J = 2$
Number of transmit antennas per BS	$N_t = 4$
Number of receive antennas per MS	$N_r = 4$
Channel model	i.i.d. (mutually independent quasi-static flat fading for all users)
Multi-stream transmission method	MIMO eigenmode transmission
Modulation	QPSK × 2 [streams/user]
Channel estimation	Ideal (Perfect CSI at TX and RX)
Transmit power per user	Equal power
Average received SNR	Equal level for all users
Desired signal to Undesired other-cell interference signal Power ratio (DUR)	Equal level for all users

III. SIMULATON MODELS

This paper evaluated the proposed MIMO transmission method by computer simulation. The simulation models are as follows.

Table 1 shows the simulation parameters. The number of BSs K is 2, and the number of MSs per cell, J, is 2. The number of antennas at each BS (transmit antennas) N_t is 4 and the number of antennas at each MS (receive antennas) N_r is 4. We assume that the channels of all users are mutually independent quasi-static flat fading channel, drawn from i.i.d. Rayleigh distribution with unit-variance for each channel entry. The BSs use MIMO eigenmode transmission for multi-stream transmission. All the BSs transmit two QPSK modulated sub-streams per user with equal powers using, respectively. In this paper, we assumed that the transmit signal power per user, the average DUR (the ratio of desired signal power to undesired outer-cell interference signal power at the receiver) and the average received SNR (Signal-to-Noise-power-Ratio) per antenna are all the same value for all MSs in order to simplify the performance evaluation. Here, the DUR was set to 15 [dB].

IV. SIMULATION RESULTS

In this section, simulation results are provided to demonstrate the Bit Error Rate (BER) performance of the proposed transmission method. The following methods were examined under the same conditions:

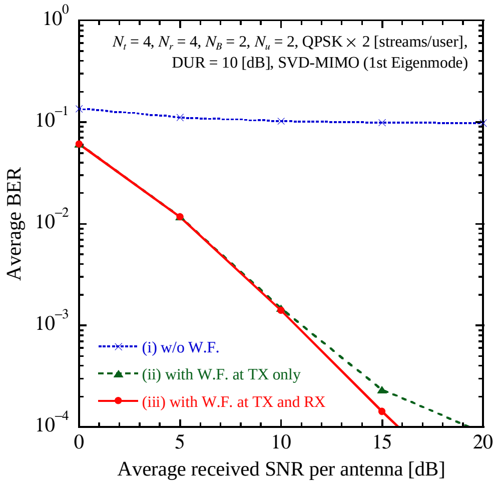
(i) Without whitening filters (“w/o W.F. ”)

(ii) With whitening filters at the transceivers (“with W.F. at TX only”)

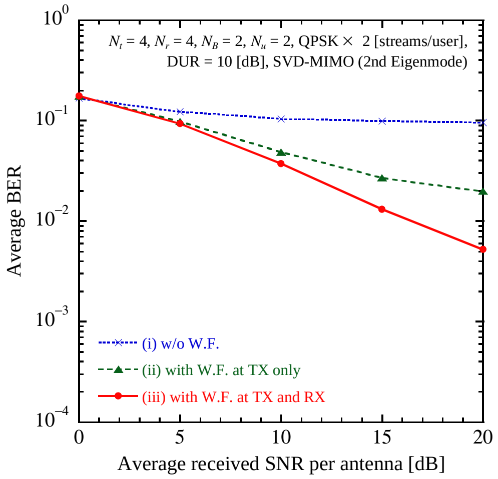
(iii) With whitening filters at both the transceivers and the receivers (“with W.F. at TX and RX”, the proposed transmission method)

Figures 4 (a) and (b) show the BER performance characteristics of the MIMO eigenmode transmission that uses 1st and 2nd eigenmodes, respectively. The dotted lines represent case (i), the dashed lines represent case (ii), and the solid lines represent case (iii). In case (iii), error floors are not seen in the SNR region from 0 [dB] to 20 [dB] because of the reduction in the inner-cell and outer-cell interference. In case (ii), no error floor is seen with 1st eigenmode transmission in the SNR region, but an error floor is seen with 2nd eigenmode transmission because the outer-cell interference was not reduced. In case (i), error floors are seen with both 1st and 2nd eigenmode transmission because the inner-cell and outer-cell interference was not reduced. For example, with 2nd eigenmode tranmission, only case (iii) can achieve the BER of 10^{-2} . Thus, whitening filters can improve the BER performance of MIMO transmission in multi-cell/multi-user environments.

Figures 5 (a) and (b) show the BER performance characteristics of the MIMO eigenmode transmission that uses 1st and 2nd eigenmodes, respectively; the parameter is DUR. Here, DUR = ∞ means that outer-cell interference does not exist. Cases (ii) and (iii) achieve the same BER characteristics because outer-cell interference is not present where DUR = ∞. On the other hand, when outer-cell interference does exist (DUR$\neq\infty$), the BER characteristics of case (ii) are different from those of case (iii). In case (ii), error floors are seen with both 1st and 2nd eigenmode transmission because the inner-cell interference was reduced while the outer-cell interference was not. On the other hand, in case (iii), error floors are not seen because the inner-cell and outer-cell interference are both reduced. However, the BER characteristics are degraded because outer-cell interference is increased when the DUR falls. At 1st eigenmode transmission with DUR = 5 dB, case (iii) can improve the required average received SNR satisfying the average BER at of 10^{-2} by about 3 dB compared with case (ii). Thus, whitening filters at both the transmitter and receiver are very effective in reducing the inner-cell and outer-cell interference for multi-cell/multi-user MIMO systems.



(a) 1st eigenmode transmission

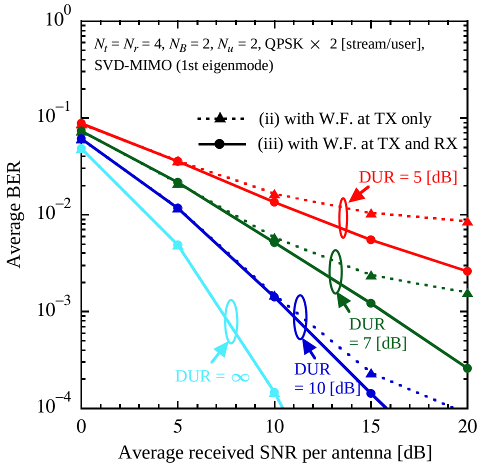


(b) 2nd eigenmode transmission

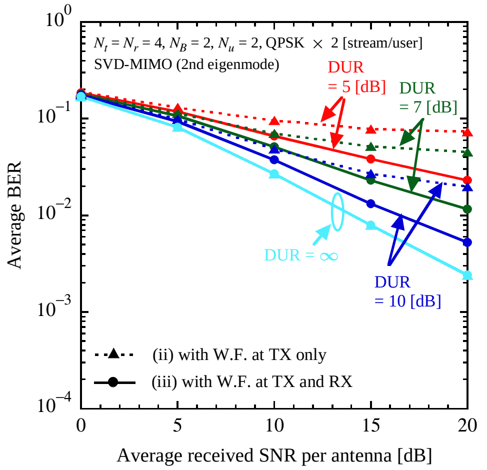
Figure 4. Average BER performance.

V. CONCLUSIONS

In this paper, we proposed a novel MIMO transmission method for the downlink of multi-user radio access systems in multi-cell environments. The proposed transmission method uses whitening filters at both the transmitter and the receiver to reduce the interference from inner and outer cells, respectively. We evaluated the proposed method by computer simulation. The simulation results clarified that the whitening filters can improve the BER characteristics of MIMO transmission in multi-cell/multi-user environments.



(a) 1st eigenmode transmission



(b) 2nd eigenmode transmission

Figure 5. Difference of BER characteristics as a parameter of DUR (Desired signal power to Undesired other-cell interference power Ratio).

REFERENCES

[1] Q. H. Spencer, A. L. Swindlehurt, and M. Haardt, “An introduction to the multi-user MIMO downlink,” IEEE Communications Magazine, vol.42, no.10, pp.60-67, Oct. 2004.

[2] R. Lai-U Choi, M. T. Ivra , R. D. Murch, and J. A. Nossek, “Joint transmit and receive multi-user MIMO decomposition approach for the downlink of multi-user MIMO systems,” Proc. IEEE VTC2003-Fall, vol.1, pp.409-413, Florida, USA, Oct. 2003.

[3] K. Fukawa, Y. Yamada, H. Suzuki and S. Suyama, “MIMO-OFDM maximum likelihood reception method in cochannel interference environments,” Proc. IEEE VTC2004-Spring, vol.4, pp.1840-1853, Milan, Italy, May 2004.

[4] T. Nishimura, Y. Takatori, T. Ohgane, Y. Ogawa, and K. Cho, “Transmit nullforming for a MIMO/SDMA downlink with receive antenna selection,” Proc. IEEE VTC2002-Fall, vol.1, Vancouver, Canada, pp.190-194, Oct. 2002.

[5] T. Ohgane, T. Nishimura, and Y. Ogawa, “Applications of space division multiplexing and those performance in a MIMO channel,” IEICE Trans. Commun. vol.E88-B, no.5, pp.1843-1851, May 2005.

[6] G. D. Golden, G. J. Foschini, R. A. Valenzuela, and P. W. Wolniansky, “Detection algorithm and initial laboratory results using V-BLAST space-time communication architecture,” Electron. Lett., vol.35, no.1, pp.14-16, Jan. 1999.

[7] S. M. Alamouti, “A simple transmit diversity technique for wireless communications,” J. Select. Areas Commun., vol.16, no.8, pp.1451-1458, Oct. 1998.

[8] A. V. Zelst, R. V. Nee, and G. A. Awater, “Space division multiplexing (SDM) for OFDM systems,” Proc. IEEE VTC2000-Spring, vol.2, pp.1070–1074, Tokyo, Japan, May 2000.

[9] S. Ting, K. Sakaguchi, and K. Araki, “Performance analysis of MIMO eigenmode transmission system under realistic channel and system conditions,” IEICE Trans. Commun., vol.E87-B, no.8, pp.2222-2232, Aug. 2004.

[10] S. Ibi, S. Sampei, and N. Morinaga, “Space-path division multiplexing technique for eigenmode transmission system,” IEICE Trans. Commun, vol.E89-B, no.6, pp.1960-1963, June 2006.

APPENDIX

We derive the whitening filters at each receiver and transmitter, $\boldsymbol{W}^H_{r,ij}$, $\boldsymbol{W}_{t,ij}$, as follows.

The receiver spatial correlation matrix including the receiver thermal noise, $\boldsymbol{R}^{(r)}_{\boldsymbol{uu},ij}$, is defined as

$$\boldsymbol{R}^{(r)}_{\boldsymbol{uu},ij} = \boldsymbol{R}^{(r)}_{\boldsymbol{xx},ij} - \boldsymbol{R}^{(r)}_{ss,ij} = \sum_{\substack{k=1\\k\neq i}}^{K} P_{s,k}\boldsymbol{G}_{k,ij}\boldsymbol{G}^H_{k,ij} + P_n\boldsymbol{I}\,, \qquad (1)$$

where

$$\boldsymbol{R}^{(r)}_{xx,ij} = E\left[\boldsymbol{x}_{ij}(t)\boldsymbol{x}^H_{ij}(t)\right], \qquad (2)$$

$$\boldsymbol{R}^{(r)}_{ss,ij} = E\left[\left\{\boldsymbol{H}_{ij}\boldsymbol{s}_i(t)\right\}\left\{\boldsymbol{H}_{ij}\boldsymbol{s}_i(t)\right\}^H\right] = P_{s,i}\boldsymbol{H}_{ij}\boldsymbol{H}^H_{ij}\,. \qquad (3)$$

In above equations, K is the number of BSs, $P_{s,k}$ is a transmit power per antenna at each BS $\#k$, P_n is the receiver thermal noise power, and $\boldsymbol{I}$ is the identity matrix. The whitening filter at each receiver $\boldsymbol{W}^H_{r,ij}$ is calculated as

$$\boldsymbol{W}^H_{r,ij} = \left(\boldsymbol{Q}_{r,ij}\boldsymbol{\Lambda}^{-1/2}_{r,ij}\right)^H, \qquad (4)$$

where $\boldsymbol{\Lambda}_{r,ij}$ and $\boldsymbol{Q}_{r,ij}$ are matrices consisting of eigenvalues and eigenvectors of the correlation matrix $\boldsymbol{R}^{(r)}_{\boldsymbol{uu},ij}$, respectively. These matrices $\boldsymbol{R}^{(r)}_{\boldsymbol{uu},ij}$, $\boldsymbol{\Lambda}_{r,ij}$, $\boldsymbol{Q}_{r,ij}$ and $\boldsymbol{W}^H_{r,ij}$ yield the following diagonalization properties.

$$\boldsymbol{Q}^H_{r,ij}\boldsymbol{R}^{(r)}_{\boldsymbol{uu},ij}\boldsymbol{Q}_{r,ij} = \boldsymbol{\Lambda}_{r,ij}\,, \qquad (5)$$

$$\boldsymbol{W}^H_{r,ij}\boldsymbol{R}^{(r)}_{\boldsymbol{uu},ij}\boldsymbol{W}_{r,ij} = \boldsymbol{I}\,. \qquad (6)$$

The transmitter regularized spatial correlation matrix of the inner-cell interference $\boldsymbol{R}^{(t)}_{\boldsymbol{uu},ij}$ for each MS $\#(i, j)$ is defined as

$$\boldsymbol{R}^{(t)}_{\boldsymbol{uu},ij} = \sum_{\substack{l=1\\l\neq j}}^{J} P_{s,il}\boldsymbol{H}'^H_{il}\boldsymbol{H}'_{il} + \boldsymbol{I}\,, \qquad (7)$$

$$\boldsymbol{H}'_{il} = \boldsymbol{W}^H_{r,il}\boldsymbol{H}_{il}\,, \qquad (8)$$

where J is the number of MSs per cell, and $P_{s,il}$ is a transmit power per antenna assigned to each MS $\#(i, j)$. The whitening filter at each transmitter $\boldsymbol{W}_{t,ij}$ is calculated as

$$\boldsymbol{W}_{t,ij} = \boldsymbol{Q}_{t,ij}\boldsymbol{\Lambda}^{-1/2}_{t,ij}\,, \qquad (9)$$

where $\boldsymbol{\Lambda}_{t,ij}$ and $\boldsymbol{Q}_{t,ij}$ are matrices consisting of eigenvalues and eigenvectors of the correlation matrix $\boldsymbol{R}^{(t)}_{\boldsymbol{uu},ij}$, respectively. These matrices $\boldsymbol{R}^{(t)}_{\boldsymbol{uu},ij}$, $\boldsymbol{\Lambda}_{t,ij}$, $\boldsymbol{Q}_{r,ij}$ and $\boldsymbol{W}_{t,ij}$ yield the following diagonalization properties.

$$\boldsymbol{Q}^H_{t,ij}\boldsymbol{R}^{(t)}_{\boldsymbol{uu},ij}\boldsymbol{Q}_{t,ij} = \boldsymbol{\Lambda}_{t,ij}\,, \qquad (10)$$

$$\boldsymbol{W}^H_{t,ij}\boldsymbol{R}^{(t)}_{\boldsymbol{uu},ij}\boldsymbol{W}_{t,ij} = \boldsymbol{I}\,. \qquad (11)$$