Adaptive Transmission in Distributed MIMO Multiplexing

Koichi Adachi†, Huiling Zhu‡, Jiangzhou Wang‡, Fumiyuki Adachi††, and Masao Nakagawa‡‡
†Institute for Infocomm Research, A*STAR, Singapore
‡Department of Electronics, University of Kent, United Kingdom
††Graduate School of Engineering, Tohoku University, Japan
‡‡Graduate School of Science and Technology, Keio University, Japan
E-mail: †kadachi@i2r.a-star.edu.sg, ‡{h.zhu, j.z.wang}@kent.ac.uk, ††adachi@ecei.tohoku.ac.jp, ‡‡nakagawa@ics.keio.ac.jp

Abstract— **Distributed antenna system (DAS) or distributed multiple-input multiple-output (MIMO) can enhance the cellular throughput performance, thanks to the largely separated multiple remote antenna units (RAU) which can experience the different large scale fading and the small scale fading. So far, much research work has been published in the DAS. However, to the authors' best knowledge, there is no research work which deals with the impact of the large scale fading effect on the throughput performance when practical data modulation, adaptive modulation, and signal detection schemes are used. How the bits should be allocated to the different RAUs is an important research topic in the DAS. In this paper, we consider two bit allocation methods: statistical channel based allocation and instantaneous channel based allocation. How the bits are allocated to each RAU are expressed by using simple equations based on statistical and instantaneous channel. Using numerical computation, how the large scale fading and bit allocation methods affect the throughput performance of distributed MIMO system are evaluated.**

Keywords-component; DAS; MIMO; interference cancellation; adaptive modulation

I. INTRODUCTION

The multiple antenna system, called multiple-input multiple-output (MIMO), has been proved to provide substantial capacity enhancement and transmission quality improvement [1]. Distributed antenna system (DAS), also called distributed MIMO, can improve the coverage of the cellular system [2]. In the DAS, a number of remote antenna units (RAUs) are connected to a base station (BS) via optical fibers and cooperate to improve the link quality. In DAS, spatially separated multiple RAUs can be used for transmission or reception of the signals. Since RAUs are located far away from each other, they experience the different large scale fading. Multiple RAUs can be used for either spatial multiplexing or spatial diversity [1].

As for the transmit diversity technique, generalized information theoretic analysis for the downlink transmission is given in [3] and it has been shown that selection diversity provides better performance than the blanket transmission (the same signal is transmitted from all RAUs) in multicell environment since selection diversity incurs less interference to other cells compared to the blanket transmission. In [4], space-time block coded (STBC) MIMO is proposed for uplink DAS. In [5], it is shown that the outage performance of the system can be enhanced greatly by adopting DAS.

In spatial multiplexing, how to allocate the information bits to each RAU is an important issue since each RAU may experience different effect of large scale fading, which is different from the centralized MIMO. In [6], spatial multiplexing technique based on large-scale fading characteristic is proposed for a zero forcing (ZF) receiver. Since the large-scale fading changes much more slowly than small scale fading, amount of the feedback information can be reduced. To the best of authors' knowledge, how the large scale fading affects the throughput performance of DAS with actual modulation schemes and the impact of the power difference among the multiple RAUs have not been fully investigated.

In this paper, we focus on spatial multiplexing. To increase the throughput of the system, adaptive modulation scheme is an effective technique [7]. In adaptive modulation scheme, modulation order can be adjusted according to the channel condition while satisfying some constraints such as target bit error rate (BER) or throughput. The modulation order may differ among the RAUs according to the average channel condition. At the mobile terminal receiver, interference canceller (IC) can be adopted as a signal detection method [8]-[10], since IC can provide good error rate performance with relatively smaller computational complexity. Based on the closed form BER expression derived in [11], the simple average BER expression is derived in fading channel and required signal-to-noise ratio (SNR) for target BER.

In this paper, first we derive simple formula for average BER according to the number of receive antennas and the average received SNR using QR-decomposition based interference canceller [10]. Then derivation of the modulation scheme is given. For simple analysis, only path loss effect is considered. The average BER performance of the distributed MIMO system is evaluated analytically and the impacts of the target SNR and target BER are evaluated. The performance comparison of the DAS is also presented by using the adaptive modulation scheme with the MIMO channel capacity. The performance comparison is shown when the modulation order is determined by the statistical channel condition (only large scale fading) and the instantaneous channel condition (both large scale fading and small scale fading).

The structure of the paper is as follows. In Section II, the system model is explained. Then, the simple approximate average BER expression is derived and performance analysis is given in Section III. Theoretical performance and numerical computation results are shown in Section IV. Section V concludes the paper.

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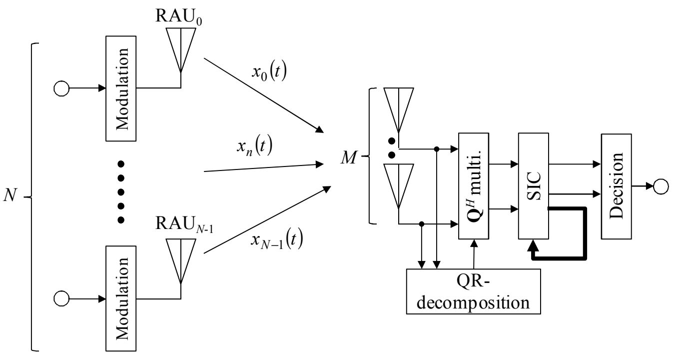


Figure 1. Downlink DAS with IC.

II. SYSTEM MODEL

The DAS downlink transmission with IC considered in this paper is shown in Fig. 1. The number of RAUs is denoted by N and the number of receive antenna by M. The signal, $\{x_n(t); n=0,\cdots,(N-1)\}$, transmitted from the n^{th} RAU $(n=0,\cdots,(N-1))$ is expressed as

$$x_n(t)=\sqrt{P_{T,n}}s_n(t), \tag{1}$$

where $P_{T,n}$ and $\{s_n(t); n=0,\cdots,(N-1)\}$ are the transmission power and the transmitted data symbol of the n^{th} RAU, respectively. Quadrature amplitude modulation (QAM) with modulation level 2^{b_n} is selected based on the channel condition between the n^{th} RAU and the mobile terminal, where b_n is the number of bits per symbol in QAM in the n^{th} RAU, and $b_n=\{0,2,4,6,8,10\}$ (the detail of the bit allocation scheme will be explained in Sect.III) [7]. $b_n=0$ indicates that no signal is transmitted from the n^{th} RAU. The constellation point for $\{s_n(t); n=0,\cdots,(N-1)\}$ is generated according to the following criterion

$$s_n(t)=\sum_{q=0}^{b_n-1}\lambda_q(-1)^{b_n^{(q)}}, \tag{2}$$

where $\{b_n^{(q)}; q=0,\cdots,(b_n-1)\}\in\{0,1\}$ is the q^{th} bit of the transmitted symbol and $\{\lambda_q; q=0,\cdots,(b_n-1)\}$ is the complex coefficient for each data modulation scheme [12]. The constellation point generated by Eq. (2) is gray coding.

Here the channel between the n^{th} RAU and the m^{th} receive antenna at the mobile terminal, denoted as $\{h_{m,n}; m=0,\cdots,(M-1), n=0,\cdots,(N-1)\}$ is assumed to be flat fading channel and does not change during the transmission. Then, the received signal at the m^{th} receive antenna, $\{y_m(t); m=0,\cdots,(M-1)\}$, becomes

$$y_m(t)=\sum_{n=0}^{N-1}\sqrt{P_{R,n}}h_{m,n}s_n(t)+\sigma_m(t), \tag{3}$$

where $\{P_{R,n}=P_{T,n}\times D_n^{-\alpha}; n=0,\cdots,(N-1)\}$ is the average received signal power from the n^{th} RAU, D_n is the distance between the n^{th} RAU and the mobile terminal, α is the path loss exponent. $\{\sigma_m(t); m=0\sim(M-1)\}$ is the additive white Gaussian noise (AWGN) with single sided power spectral density of N_0.

M-dimensional received signal vector $\mathbf{y}(t)=(y_0(t)\ \cdots\ y_m(t)\ \cdots\ y_{M-1}(t))^T$ can be expressed as

$$\mathbf{y}(t)=\mathbf{HPs}(t)+\boldsymbol{\sigma}(t), \tag{4}$$

where $\mathbf{H}$ is the M-by-N channel matrix, $\mathbf{P}$ is the N-by-N received signal power diagonal matrix, $\mathbf{s}(t)$ it the N-by-1 transmitted signal vector, and $\boldsymbol{\sigma}(t)$ is the M-by-1 noise vector.

III. PERFORMANCE ANALYSIS

A. Avearge BER Perforamnce

Maximum likelihood detection (MLD) [13] provides the best signal detection quality among the various signal detection schemes, however, its computational complexity becomes prohibitively high in high order modulation. On the other hand, QR-decomposition based signal detection method is computationally efficient while providing good performance [14]. Thus in this paper, we adopt successive interference cancellation (SIC) utilizing QR-decomposition. By using QR-decomposition, the channel matrix between the mobile terminal and the multiple RAUs can be decomposed into upper triangular matrix. Then based on the characteristic of the upper triangular matrix, signal detection and IC can be performed. In SIC with QR-decomposition, the number of the surviving symbol replica candidates has a critical effect on the performance, since the diversity order of the signal which is detected in the i^{th} interference cancellation stage can obtain $(M-1)^{\text{th}}$ spatial diversity. However, for the simplicity of the analysis, only single surviving symbol replica candidate is considered at each detection stage.

First, the received signal is normalized by the square root of the power of the received signal from the n=0$^{\text{th}}$ RAU as

$$\begin{aligned}\tilde{\mathbf{y}}(t)&=1/\sqrt{P_{R,0}}\times\mathbf{y}(t)\\&=\mathbf{H}\tilde{\mathbf{P}}\mathbf{s}(t)+\tilde{\boldsymbol{\sigma}}(t)\end{aligned}, \tag{5}$$

where

$$\tilde{\boldsymbol{\sigma}}(t)=1/\sqrt{P_{R,0}}\times\boldsymbol{\sigma}(t) \tag{6a}$$

$$\tilde{\mathbf{P}}=diag\left(1\ \cdots\ \sqrt{P_{R,n}/P_{R,0}}\ \cdots\ \sqrt{P_{R,N-1}/P_{R,0}}\right) \tag{6b}$$

with

$$P_{R,n}/P_{R,0}=\left(P_{T,n}/P_{T,0}\right)\times\left(D_n/D_0\right)^{-\alpha}. \tag{7}$$

Define new variables $\{p_n; n=0,\cdots,(N-1)\}$ and $\{d_n; n=0,\cdots,(N-1)\}$ as the ratio of the transmit power of the n^{th} RAU to the 0$^{\text{th}}$ RAU and the distance ratio from the n^{th} RAU to the 0$^{\text{th}}$ RAU as

$$\begin{cases}p_n=P_{T,n}/P_{T,0}\\d_n=D_n/D_0\end{cases}. \tag{8}$$

By using (8), (6b) can be rewritten as

$$\tilde{\mathbf{P}}=diag\left(1\ \cdots\ \sqrt{p_n d_n^{-\alpha}}\ \cdots\ \sqrt{p_{N-1}d_{N-1}^{-\alpha}}\right). \tag{9}$$

QR-decomposition is performed on channel matrix $\mathbf{H}$ as $\mathbf{H}=\mathbf{QR}$ where $\mathbf{Q}$ is the M-by-N unitary matrix and $\mathbf{R}$ is the N-by-N upper triangular matrix.

The orthogonalized received signal vector, $\hat{\mathbf{y}}(t)=(\hat{y}_0(t)\ \cdots\ \hat{y}_n(t)\ \cdots\ \hat{y}_{N-1}(t))^T$, is obtained by multiplying $\mathbf{Q}^H$ from left side to $\tilde{\mathbf{y}}(t)$ as

$$\hat{\mathbf{y}}(t)=\mathbf{Q}^H\tilde{\mathbf{y}}(t). \qquad (10)$$

By substituting (5) into (10), we have

$$\begin{aligned}\mathbf{Q}^H\tilde{\mathbf{y}}(t)&=\mathbf{Q}^H\mathbf{H}\tilde{\mathbf{P}}\mathbf{s}(t)+\mathbf{Q}^H\tilde{\boldsymbol{\sigma}}(t)\\&=\mathbf{R}\tilde{\mathbf{P}}\mathbf{s}(t)+\hat{\boldsymbol{\sigma}}(t)\end{aligned}, \qquad (11)$$

where $\hat{\boldsymbol{\sigma}}(t)=(\hat{\sigma}_0(t)\ \cdots\ \hat{\sigma}_n(t)\ \cdots\ \hat{\sigma}_{N-1}(t))^T$ is the N-by-1 equivalent noise vector and

$$\hat{\sigma}_n(t)=\mathbf{q}_n^H\tilde{\boldsymbol{\sigma}}(t) \qquad (12)$$

with $\mathbf{q}_n$ being the n^{th} column of unitary matrix $\mathbf{Q}$.

By defining the new upper triangular matrix $\tilde{\mathbf{R}}$ as $\tilde{\mathbf{R}}=\mathbf{R}\tilde{\mathbf{P}}$ we have

$$\hat{\mathbf{y}}(t)=\tilde{\mathbf{R}}\mathbf{s}(t)+\hat{\boldsymbol{\sigma}}(t). \qquad (13)$$

In the 0^{th} signal detection stage of QR-decomposition based SIC, there is no interference from the other $(N-1)$ RAUs since $\tilde{\mathbf{R}}$ is the upper triangular matrix. Thus, we have

$$\hat{y}_{N-1}(t)=\tilde{r}_{N-1,N-1}s_{N-1}(t)+\hat{\sigma}_{N-1}(t). \qquad (14)$$

where $\tilde{r}_{n,n}$ is the element at the n^{th} row and n^{th} column of $\tilde{\mathbf{R}}$.

The noise variance is computed as

$$E\left[\left|\hat{\sigma}_n(t)\right|^2\right]=\mathbf{q}_n^H E\left[\tilde{\boldsymbol{\sigma}}(t)\tilde{\boldsymbol{\sigma}}^H(t)\right]\mathbf{q}_n, \qquad (15)$$

where $(.)^H$ denotes conjugate operation.

Since the noise at each receive antenna is uncorrelated, i.e., $E[\sigma_n(t)\sigma_{n'}^*(t')]=N_0/T_s\times\delta(n-n')\delta(t-t')$ with $\delta(.)$ being delta function, and T_s being the symbol period, we have

$$E\left[\tilde{\boldsymbol{\sigma}}(t)\tilde{\boldsymbol{\sigma}}^H(t)\right]=2\times\bar{\gamma}_0^{-1}\times\mathbf{I}_M, \qquad (16)$$

where $E[.]$ denotes the ensemble average operation and $\bar{\gamma}_0=P_{R,0}\times T_s/N_0$ is the average received SNR of the signal from n=0th RAU. Since the column vector of unitary matrix is orthonormal, i.e., $\mathbf{q}_n^H\mathbf{q}_n=1$, we have

$$E\left[\left|\hat{\pi}_n(t)\right|^2\right]=\mathbf{q}_n^H\left(2\cdot\bar{\gamma}_0^{-1}\times\mathbf{I}_M\right)\mathbf{q}_n=2\times\bar{\gamma}_0^{-1}. \qquad (17)$$

The instantaneous received SNR of the signal transmitted from the $n=(N-1)^{\text{th}}$ RAU becomes

$$\gamma_{N-1}=\bar{\gamma}_0\times p_{N-1}d_{N-1}^{-\alpha}\times\left|r_{N-1,N-1}\right|^2\times E\left[\left|s_{N-1}(t)\right|^2\right]. \qquad (18)$$

$\{|r_{n,n}|^2;n=0,\cdots,(N-1)\}$ is the chi-squared distribution with the degrees of freedom of $2(M-n)$ and $\{r_{m,n};m<n\}$ is the complex Gaussian random variable with $|r_{m,n}|^2$ being the chi-squared distribution with the degrees of freedom of 2 [15].

1) Statistical Channel Based Allocation Method

The probability density function (PDF) of $\{\gamma_n;n=0,\cdots,(N-1)\}$ becomes

$$f(\gamma_n)=\frac{1}{\bar{\gamma}_n\times\Gamma(M-n)}\left(\frac{\gamma_n}{\bar{\gamma}_n}\right)^{(M-n-1)}\exp\left(-\frac{\gamma_n}{\bar{\gamma}_n}\right), \qquad (19)$$

where $\bar{\gamma}_n$ is the average received signal power given as

$$\bar{\gamma}_n=\bar{\gamma}_0\times p_n\times d_n^{-\alpha} \qquad (20)$$

and $\Gamma(.)$ is *Gamma function* [16].

If the modulation scheme and the transmission power of the n^{th} RAU are determined to satisfy the required BER, say 10^{-3}, interference cancellation in SIC can be correctly performed as

$$\begin{aligned}\hat{y}_n(t)&=\left\{r_{n,n}s_n(t)+\sum_{n'=n+1}^{N-1}\sqrt{p_{n'}d_{n'}^{-\alpha}}\times r_{n,n'}s_{n'}(t)+\hat{\sigma}_n(t)\right\}\\&\quad-\sum_{n'=n+1}^{N-1}\sqrt{p_{n'}d_{n'}^{-\alpha}}\times r_{n,n'}\tilde{s}_{n'}(t)\\&\approx r_{n,n}s_n(t)+\hat{\sigma}_n(t)\end{aligned} \qquad ,(21)$$

where $\{\tilde{s}_{n'}(t);n'=(n+1),\cdots,(N-1)\}$ is the interference replica obtained in the n'^{th} stage.

Accordingly, the instantaneous received SNR of the signal transmitted from the n^{th} RAU becomes

$$\gamma_n\approx\bar{\gamma}_0\times p_n d_n^{-\alpha}\times\left|r_{n,n}\right|^2\times E\left[\left|s_n(t)\right|^2\right]. \qquad (22)$$

Based on the received SNR, modulation order is selected from 2^{b_n}-QAM constellation.

It has been shown that the BER of 2^{b_n}-QAM in AWGN channel for BER less than 10^{-3} can be well approximated in closed form as [11]

$$P_{b,n}\approx\frac{1}{5}\exp\left(\frac{-1.6\times\gamma_n}{2^{b_n}-1}\right). \qquad (23)$$

The average BER in the fading environment is calculated by averaging the above formula for all possible value of γ_n as

$$\bar{P}_{b,n}=\frac{1}{\bar{\gamma}_n\Gamma(M-n)}\int_0^\infty P_{b,n}\exp\left(-\frac{\gamma_n}{\bar{\gamma}_n}\right)\times\left(\frac{\gamma_n}{\bar{\gamma}_n}\right)^{(M-n-1)}d\gamma_n. \qquad (24)$$

After some mathematical manipulation, we have the following expression for average BER performance.

$$\bar{P}_{b,n}=\frac{1}{5}\times\left(\frac{1.6}{2^{b_n}-1}\bar{\gamma}_n+1\right)^{-M+n}. \qquad (25)$$

Then, the modulation order b_n can be determined by the following equation.

$$b_n=\left\lfloor\log_2\left(\frac{1.6\bar{\gamma}_n}{\left(5\bar{P}_{b,n}\right)^{1/(-M+n)}}+1\right)\right\rfloor. \qquad (26)$$

where $\lfloor x\rfloor$ denotes the largest integer smaller than or equal to x. In the case of statistical channel based allocation method, the modulation order of each RAU is determined based on the average BER and SNR value.

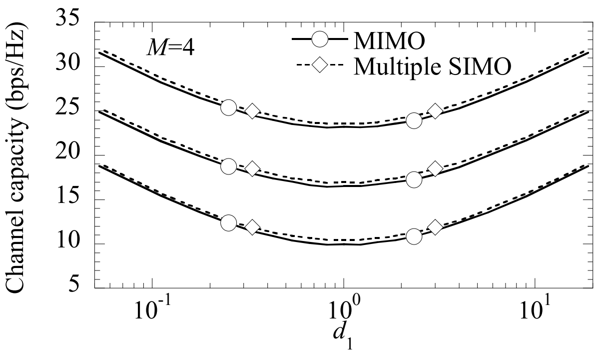


Figure 2. Channel Capacity of MIMO and Multiple SIMO.

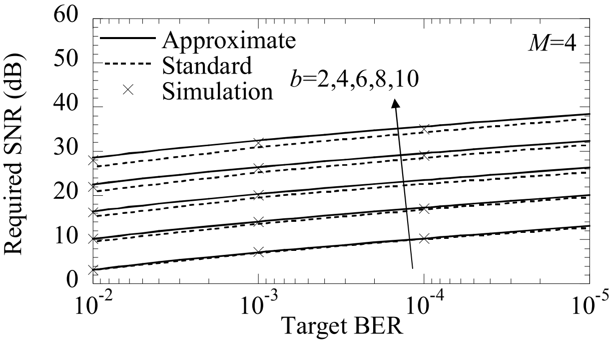


Figure 3. Required SNR to achieve target BER.

2) *Instantaneous Channel Based Allocation Method*

From (23), the achievable instantaneous throughput for the n^{th} RAU while satisfying required BER $P_{b,n}$ with received instantaneous SNR γ_n is given as

$$b_n = \left\lfloor \log_2\left(\frac{-1.6\times\gamma_n}{\ln\left(5P_{b,n}\right)}+1\right)\right\rfloor, \tag{27}$$

where $\{\gamma_n; n=0,\cdots,(N-1)\}$ is given as

$$\gamma_n = \bar{\gamma}_0 \times p_n d_n^{-\alpha} \times \left|r_{n,n}\right|^2 \times E\left[\left|s_n(t)\right|^2\right]. \tag{28}$$

Since γ_n depends on not only the average received SNR but also the instantaneous channel matrix, the mobile terminal construct the N! channel matrices and sum data rate is calculated as

$$b = \sum\nolimits_{n=0}^{N-1} b_n\ . \tag{29}$$

Then, based on the channel matrix which provides the highest throughput, the modulation order from each RAU is fed back to RAUs.

B. *Channel Capacity*

When the adaptive modulation scheme is used, the achievable throughput is given by the channel capacity. The channel capacity of MIMO system is given by

$$C = E\left[\log_2 \det\left(\mathbf{I}_M + \mathbf{\Omega}\mathbf{H}\mathbf{H}^H\right)\right], \tag{30}$$

where det($\mathbf{X}$) denotes the determinant of matrix $\mathbf{X}$ and $\mathbf{\Omega} = \mathbf{PP}$. In the MIMO channel capacity, it is difficult to know that how much information is transmitted from each RAU, since MIMO channel capacity indicates the sum rate of the multiple signals. Thus, MIMO channel can be treated as multiple SIMO channel as

$$C \approx \sum\nolimits_{n=0}^{N-1} \log_2\left(1 + P_{R,n} \times \sum\nolimits_{m=0}^{M-1}\left|h_{m,n}\right|^2\right). \tag{31}$$

Figure 2 shows the MIMO channel capacity calculated from (30) and the multiple SIMO channel capacity calculated from (31). It can be seen from the figure that the difference between them is relatively small. Thus in the following performance evaluation, (31) is used for performance measure.

IV. NUMERICAL RESULTS

In this section, representative numerical and simulation results are presented. For the simplicity of the evaluation, the number of RAUs is set $N=2$, and the number of receive antennas, M, is 4. 2^b -ary QAM modulation is used. Path loss exponent α is fixed to 3, unless noted otherwise. The signal detection order is determined so that the achievable throughput becomes larger.

From (25), the required average SNR of the n^{th} RAU, $\bar{\gamma}_{req,n}$, to achieve target BER $P_{b,trgt}$ is given by

$$\bar{\gamma}_{req,n} = \left(\left(5P_{b,trgt}\right)^{\frac{1}{-M+n}} - 1\right) \times \left(\frac{\left(2^{b_n}-1\right)}{1.6}\right). \tag{32}$$

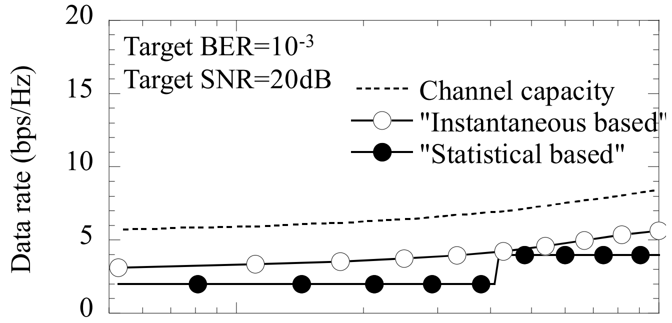
The standard formula of the average BER performance of 2^b -ary QAM is given by [17]

$$\bar{P}_{b,std} = E\left[\frac{2}{b}\left(1-\frac{1}{\sqrt{2^b}}\right) \times erfc\left(\sqrt{\frac{1.5}{2^b-1}\gamma}\right)\right], \tag{33}$$

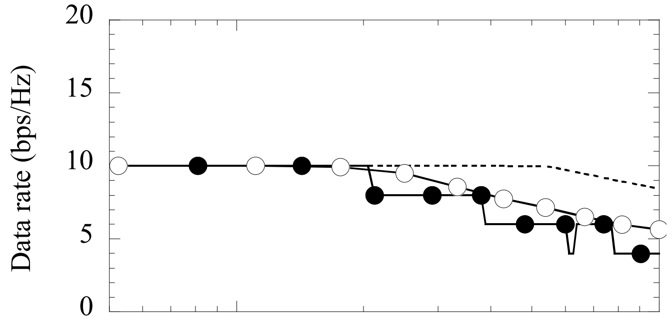
where $erfc(.)$ is the complementary error function [16].

Figure 3 shows the required SNR to achieve the target BER for various modulation schemes computed from (32) denoted by analysis and obtained from the numerical results of standard formula (33) denoted by "standard", and simulation as a function of the target BER. It can be seen from the figure that, the required SNR computed from (32) can well agree with the required SNR obtained from computer simulation. Thus, in the following simulation, (32) is used for determining the required average SNR to achieve the target BER and only the analytical results will be shown in the figures.

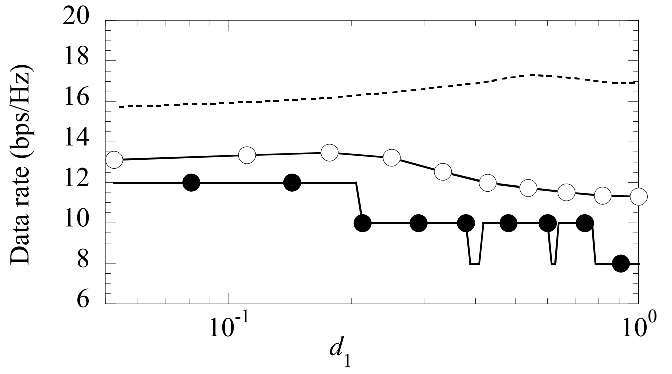
Figure 4 shows the impact of distance ratio d_1 on the data rates (bps/Hz) of each RAU and the sum of the data rate of two RAUs. Target BER $\bar{P}_{b,n}$ is set to 10^{-3} and the target SNR at reference distance $D_n = 1$ for $n = 0,1$ is set to 20dB. We upper bound the channel capacity per RAU to 10 (bps/Hz) which is corresponding to the data rate of 1024QAM with $b=10$. The bit allocation methods are "instantaneous channel based allocation" which allocates the bit to each RAU according to the instantaneous channel condition using (27) and "statistical channel based allocation" which allocates according to the large scale fading using (26). In the case of "instantaneous channel based allocation", it is quite difficult to obtain the



(a) RAU0



(b) RAU1



(c) Sum data rate

Figure 4. Performance difference owing to the allocation method.

required SNR based on the target BER if not possible since the probability density function of the diagonal elements of **R** changes [15], we resort to the computer simulation. From the figure it can be seen that when mobile station is located close to one of the RAU, the throughput difference between "instantaneous based ranking" provides and "statistical based ranking" does is relatively small. On the other hand, as the mobile station moves away from one of the RAUs, i.e., approaches to the middle of two RAUs, the throughput difference becomes larger. From these results, although the feedback information to decide the modulation order from mobile station becomes larger in the case of "instantaneous channel based allocation" compared to "statistical channel based allocation", the throughput performance can be significantly improved by allocating the bits according to the instantaneous channel condition. For example, if the number of modulation order is 6, then feedback information of 3 bps/Hz is required for the case of "instantaneous channel based allocation". Although the time/frequency correlation of the channel can be used to reduce the feedback information, the advantage of "instantaneous channel based ranking" over "statistical channel based ranking" becomes smaller.

V. CONCLUSION

In this paper, we considered the adaptive modulation method in spatial multiplexing for downlink DAS, where QR-decomposition based successive interference canceller is used at the mobile terminal. The bit allocation method is an important factor in the DAS systems. We considered two bit allocation methods: statistical channel based allocation and instantaneous channel based allocation. The modulation order is selected based on the average received signal power and the target BER. By using numerical and computer simulation, it has been shown that there is some performance degradation at the middle of two RAUs, statistical channel based allocation method may reduce the required feedback information compared to the instantaneous channel based allocation method.

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