Node Pair Selection Scheme for MIMO Multiuser System Using Repeated Application of Stable Matching Algorithm

Testuki Taniguchi and Yoshio Karasawa
The Department of Communication Engineering and Informatics
Advanced Wireless Communication research Center (AWCC)
The University of Electro-Communications (UEC)
Tokyo, 182-8585 Japan
Email: taniguch@ee.uec.ac.jp, karasawa@radio3.ee.uec.ac.jp

***Abstract*—This study attempts an extension of previously proposed node pair selection scheme in multiuser Multiple Input Multiple Output (MIMO) communication network based on stable matching problem to the case in which one node can be a candidate of plural pair nodes. To cope with such a situation, repeated application of stable matching algorithm is considered, where total pairs are determined through some stages, each of which selects subset of pair nodes. Thanks to the polynomial complexity of matching algorithm, the proposed procedure still keeps low computational cost. Applications considered here are multiple point to multiple point multiuser system and the simultaneous selection of source-relay-destination pairs. Computer simulations are carried out to investigate the possibility of the effectiveness of the proposed concept. It has been shown that the proposed method is useful for the efficient node pair selection in multiple point system where one source node can transact plural destinations.**

Keywords–Node selection; Multiple Input Multiple Output (MIMO) network; multiuser; interference channel; stable matching.

I. INTRODUCTION

Recently, MIMO interference channel [1] got attention since its utilization is widely found in many applications in communication networks [2]-[4]. Different from conventional multiuser MIMO, this system consists of plural nodes, as the source and destination, and the total performance depends on the node pair selection. The best way is the exhaustive search of the pairs with the best performance (since the number of node pairs is limited, the best solution could be always found at the expense of heavy computational burden), but it normally requires a considerable computation. On the contrary, fixed pair selection needs no computation and sometimes it could be a reasonable choice; but, under the channel variation, performance of this scheme is degraded.

In a previous work [5], we have presented a node pair selection scheme in relay-aided multi-point MIMO communication system based on stable matching theory (so called "stable marriage problem"). The preference of target node is first determined based on some kinds of metrics like the maximum eigenvalue, norm; it has been shown that the solution using Gale-Shapley algorithm [6] can improve the performance compared with the fixed pair case with low computational cost. This method is putting the importance on the simpleness of the procedure; the node pair selection is simply applied to each of two hops separately. But, we still have many applications in the area of communication engineering in which the conventional approach cannot be directly utilized. The typical example is the case where the source nodes can communicate with plural destinations which is found in multi-cellular communication. As one of such cases, this study attempts the extension of node pair selection scheme presented in [5] to the case in which one candidate can conform node pair with plural pair nodes. For this aim, repeated application of the stable matching algorithm is considered, where total pairs are determined through some stages, each of which selects subset of pair nodes. Here, we inspect the possibility of such algorithms through two types of problems including the above-mentioned typical example of MIMO interference channel.

The organization of the rest of this paper is as follows: in Section II, the system model of two types of communication scenario is shortly given. In Section III, the detail of the proposed node pair selection scheme is described. Section IV evaluates the possibility of the effectiveness of the proposed approach through computer simulations. Finally, Section V provides the concluding remarks of this study and the future works.

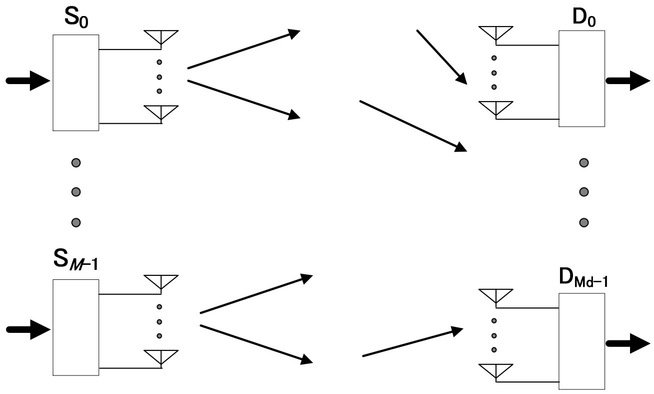
II. SYSTEM MODEL

This section describes the two models of communication systems considered in this work.

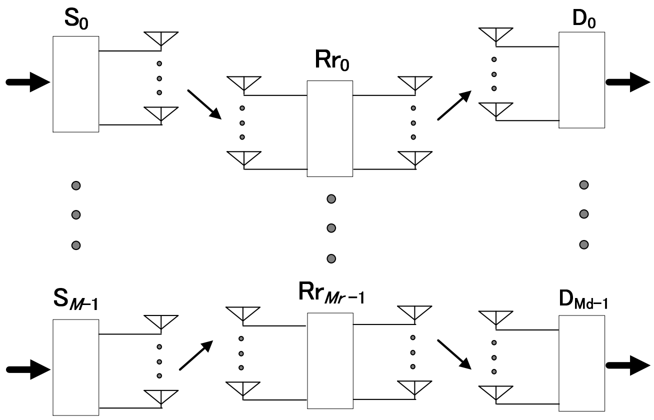
A. Fundamental System

This fundamental system has the typical structure of multiple point to multiple point multiuser system, as shown in Figure 1 (a), consisting of M-sources ($\{\mathrm{S}_m;\ m = 0,\ \cdots .M-1\}$, S_m is equipped with $N_{s,m}$ antennas) and M_d-destination ($\{\mathrm{D}_{m_d};\ m_d = 0,\ \cdots .M_d-1\}$, D_{m_d} has $N_{d,m}$ antennas) nodes (this study assumes $M \leq M_d$). The channel between S_m and D_{m_d} is represented by $N_{d,m}$-by-$N_{s,m}$ matrix $H_{d,m_d,s,m}$ whose (n_d, n_s)-th element is a complex-valued response between n_s-th and n_d-th antennas of source and destination. Source S_m transmits L_m data streams $\{s_{m,\ell}(t);\ \ell = 0,\ \cdots,\ L_m-1\}$ to destination D_{d_m} ($d_m \in \mathbb{Z}[0, M_d-1]$) which forms node pair with S_m through MIMO channel $H_{d,d_m,s,m}$, where weight vector $\boldsymbol{w}_{s,m,\ell}$ with $N_{s,m}$-dimension is used for the transmission of the ℓ-th data stream $s_{m,\ell}(t)$, and weight vector $\boldsymbol{w}_{d,d_m,\ell}$ with N_{d,d_m}-dimension is used for the production of ourput $\hat{s}_{m,\ell}(t)$. If the relation of source and destination is one-to-one, stable matching procedure can be directly applied for the determination of the node pairs. But here, we assume that S_m can transact plural destinations ($\mathrm{D}_{d_m,0},\ \cdots,\ \mathrm{D}_{d_m,M_{d,m}-1}$). The modification in such a case is described in the following section.

 ISBN: 978-1-61208-368-1



(a) Fundamental system. Souce S_m can communicate with plural ($M_{d,m}$) destinations, while every destinations have only one pair source.



(b) Relay-aided system. Each of source, relay, and destination have one-to-one relation.

Figure 1. Model of multiple point to multiple point communication system.

B. Relay-Aided System

The construction of relay-aided system in this study is shown in Figure 1 (b). The difference from the previous model is in two points; (i) the system has Amplify and Forward (AF) relays $\{\mathrm{R}_{m_r};\ m_r = 0, \cdots, M_r - 1\}$ with N_{r,m_r} antennas ($M \leq M_r \leq M_d$), and (ii) one-to-one connection among nodes (this is not mandatory, but here, we use this assumption to measure the effect of each scenario separately). Relay R_{r_m} receives signal from source S_m, produces output $s_{r,m,\ell}(t)$ (it is the estimate of $s_{m,\ell}(t)$ corrupted by noise) using weight vector $\boldsymbol{w}_{r,r,m,\ell}$ and retransmits it to destination D_{d_m} using weight vector $\boldsymbol{w}_{r,t,m,\ell}$. Hence, we need to determine M node pairs of source, relay, and destination; one method has been presented in [5] and another one is described in the next section.

C. System Design

In this study, weight vectors which appear in the two previous subsections are derived by channel inversion technique [7] (but it is applied to the product of the channel and destination weight, where destination weight is designed by singular value decomposition of the target channel as follows). Namely, the receiver vector of R_{r_m} detecting the ℓ-th data stream is derived as the right singular vector of $H_{x,m,y,n}$ (((x, y) = (s, r) or (r, d)) for the fundamental system, and ((x, y) = (s, d) for the relay-aided system) corresponding to the ℓ-th largest singular value. Then transmit weight matrix is calculated by $\boldsymbol{w}_{x,m} = (H_{y,n,x,m} V_{0,m})^{-}$, where (($x, y$) = ($s, r$) or ($r, d$)) or ($s, d$) and A^{-} denotes the pseudo-inverse of matrix A. The columns of $V_{0,m}$ spans kernel of $H_{y,-m,x,m}$, where $H_{y,-m,x,m}$ is given by removing $H_{y,m,x,m}$ from $[H_{y,0,x,m}, \ \cdots, \ H_{y,M-1,x,m}$. This design method is adopted because (i) the design method with the best performance is not the main topic of this study, and (ii) it can avoid the problem of energy allocation, and suitable for the evaluatin of the pure effect of node selection.

III. Node Pair Selection

This section describes node pair selection schemes corresponding to each of two models shown in Section II.

A. Fundamental System

The total procedure consists of four steps, namely, (i) calculation of preference function $f_{x,n,y,m}$, (ii) determination of preference order list $\mathcal{P}_{x,m}$ from $f_{x,n,y,m}$, (iii) node pair selection based on $\mathcal{P}_{x,m}$, and (iv) removal of nodes which already have maximum number of pair nodes. The difference from the conventional approach is in that those steps are repeated to cope with the support of plural target nodes. The detailed manipulations are as follows:

(i) First, preference function $f_{x,n,y,m} = f_{y,m,x,n}$, ($x, y = s, d, \ x \neq y$) is defined as a metric which shows how node x prefers node y. In this study, it is calculated based on the channel condition, since it is considered as an adequate index of the internode connection.

Here, we consider five types of metrics in the below.

(a) Fixed: Node pairs are fixed (e.g., $d_m = m$), which is equivalent to the case without node pair selection.

(b) Largest Eigenvalue: Preference function is $f_{d,n,s,m} = \lambda_0$, where λ_0 is the largest eigenvalue of $H_{d,n,s,m}$.

(c) Approximated Sum Capacity: Preference function is $f_{d,n,s,m} = \sum \log_2 (1 + \lambda_k)$, where λ_k is the k-th largest eigenvalue of $H_{d,n,s,m}$.

(d) Norm: Preference function is $f_{d,n,s,m} = \|H_{d,n,s,m}\|_F$ (approximation of sum capacity).

(e) Absolute Sum: Preference function is $f_{d,n,s,m} = \sum_{p,q} |H_{d,n,s,m,p,q}|$, where $A_{p,q}$ is the (p,q)-th element of matrix A (simple approximation of sum capacity).

Among those, (b), (c) are based on eigenanalysis, (d) needs multiplication, and (e) does not require either, hence the computational burden of (e) becomes much lower. □

(ii) Second, the preference order list $\mathcal{P}_{x,m} = \{p_{s,m,0} \succ \cdots \succ p_{s,m,N-1}\}$ ($N = M, M_d$) is obtained, where $x \succ y$ denotes that x is preferred to y. The list is made simply by the relation if $f_{x,p,y,m} > f_{x,q,y,m}$, then $p_{s,m,p} \succ p_{s,m,q}$. □

(iii) Third, the Gale-Shapley algorithm (for the detail of this algorithm, see [5] or [6]) is utilized to determine the node pairs based on preference order list. It is assured that the algorithm converges to stable pairs within polynomial time. Then, if S_m is connected to a destination with the largest preference function, they are recognized as a pair. If not, this source node proceeds to next iteration to search for a better candidate of the pair node. □

(iv) Fourth, if the number of pair nodes for node x_m has reached its maximum (here, $M_{d,m}$ for S_m, and 1 for all destinations), then x_m is removed from active nodes (active node means a node which has pair nodes less than its maximum and further looking for its next pair) and the preference order list of all active nodes. Then the procedure goes back to step (i), and repeats steps until no active source node is left. □

The above procedure requires repetition of original algorithm, but still keeps the polynomial computational time. Together with the fact that the node pair selection itself demandes just changing list elements several times without any multiplication, once the metric is given, the computational cost is very low.

B. Relay-Aided System Design

In the previous work [5], we have considered separate node pair selection in each of source-relay and relay-destination links, but another idea is to choose both link simultaneously. This scheme can be achieved by a similar procedure, as shown in Section III-A; this is the reason we consider this application here. The aim dealing with relay-aided system is to inspect which is better choice. In addition, the above idea has a possibility to be extended to multihop multinode systems, where method of [5] is not used; since it can include different number of hops depending on the routing. But here, we concentrate on the inspection of the effect in one-to-one relaying application.

The pair selection steps are shown below (for the discrimination from the step number (i), (ii), etc., in Subsection III-A, here, we use (1), (2), etc.).

(1) Consider a set of channels $\{H_{d,n,r,k,s,m} = H_{d,n,r,k}H_{r,k,s,m}\}$ and define preference function $f_{x,n,y,m,k} = f_{y,m,k,x,n}$, which can be regarded as a fundamental system of MM_r source nodes and M_d destinations. □

(2) Preference order list $\mathcal{P}_{x,m} = \{p_{y,m,0} \succ \cdots \succ p_{y,m,N-1}\}$ $(N = MM_r, M_d)$ is made, and node pair selection is carried out in the same manner as step (ii) of the previous section. □

(3) If the pairs of different destinations contain *same source or relay*, then the destination with larger preference function is chosen. After that, the source, relay, and destinations which already have pair nodes are removed from active nodes. The elements concerning those removed nodes are concurrently removed from preference list of all active nodes, and steps (1)∼(3) are repeated until no active source node is left. □

This procedure is assured to converge since that of each iteration is guaranteed. The comparison with the conventional approach is made in the next section.

IV. COMPUTER SIMULATION

Default simulation conditions are enumerated in Table I. In this section, computer simulations are carried out to investigate the effectiveness of the procedures described in Section III.

TABLE I. DEFAULT SIMULATION CONDITIONS.

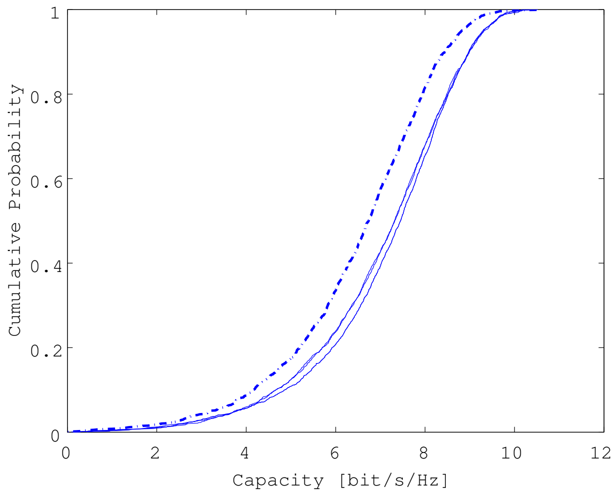
User Number	$M = 3$
Node Number	Source $M = 3$ Relay $M_r = 5$ Destination $M_d = 8$
Antenna Number	Source $N_{s,m} = \begin{cases} 6 & (L_m = 1) \\ 12 & (L_m = 2) \end{cases}$ Relay $N_{r,m} = 6$ Destination $N_{d,m} = 2$
Data Stream Number	$L_m = 2$
Modulation	QPSK
Relaying Scheme	Amplify and Forward (AF) half-duplex
Relay SNR	$\mathrm{SNR}_{r,m} = 5 \sim 30$ dB (default : 20dB)
Destination SNR	$\mathrm{SNR}_{d,m} = 5 \sim 30$ dB (default : 20dB)
Fading (fundamental)	$H_{d,n,s,m}$ i.i.d. Quasistatic Rayleigh
Fading (relay-aided)	$H_{d,n,s,m}$ ignored $H_{r,n,s,m}$, $H_{d,n,r,m}$ i.i.d. Quasistatic Rayleigh

The evaluation is by sum capacity represented by $C_m = \sum_\ell \log_2(1 + \gamma_{m,\ell})$ for the m-th user, where $\gamma_{m,\ell}$ is the Signal to Interference plus Noise Ratio (SINR) of the ℓ-th data stream of the m-th user, which should be discriminated from Signal to Noise Ratio (SNR) $\mathrm{SNR}_{x,m}$ $(x = r, d)$ defined as energy ratio of transmitted signal and the receiver noise. The modulation scheme is QPSK (a fundamental scheme with PAM in both of real and imaginary axes), but the effectiveness of the proposed scheme is not affected by the choice of modulation.

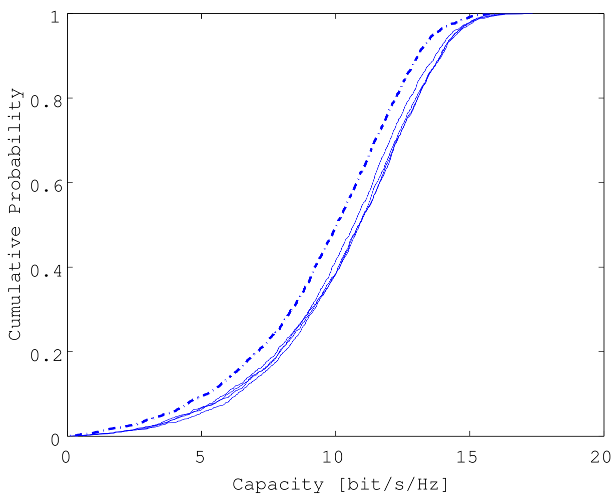
In the fundamental system (Section III-A), the number of users is $M = 3$, while that of destination is $M_d = 8$, where all of them are equipped with $N_{s,m} = 6$ (singlestream) or $N_{s,m} = 12$ (multistream) and $N_{d,m} = 2$ antennas, respectively. The number of data streams is $L_m = 1$ or 2, and one source node supports two users, hence $M_{d,m} = 2$. In the relay-aided system (Section II-B), where $N_{r,m} = 6$ and other conditions are same as multistream transmission in the fundamental case, the first hop is assumed not Ricean (LOS: Line Of Sight), but Rayleigh fading with unit variance since (i) there are applications this assumption applies [8], and (ii) in case of LOS, it is clear that the effect of node pair selection in the first hop is small when direct path is dominant.

Under those simulation conditions, the mean statistics are calculated using 2,000 samples of fading channels.

Figure 2 shows empirical distribution functions of sum capacity in fundamental system. Here, because of the symmetry of the channels among nodes, the curves of mean value over $\sum M_{d,m}$ users are considered. In both subplots for (a) singlestream ($L_m = 1$) and (b) multistream ($L_m = 2$), the curves of node pair selection (four solid lines corresponding to the metrics (b)sim(e)) overcome that of fixed case (broken line corresponding to the metric (a)), which shows the proposed approach in Section II-A has certain effectiveness. (Since the curves of (b)∼(e) overlap and not identifiable, all of them are written by solid line. For the comparison of (b)∼(e), see Figure 3.) The amount of improvement seems not so large, but we should remark that this is achieved only by the exchange of node pairs, and in particular adopting absolute sum preference function, no multiplications are required. In both figures, one of preference functions (in (a) absolute sum,



(a) Singlestream ($L_m = 1$).



(b) Multistream ($L_m = 2$).

Figure 2. Distribution function of capacity in fundamental system shown in Figure 1 (a).

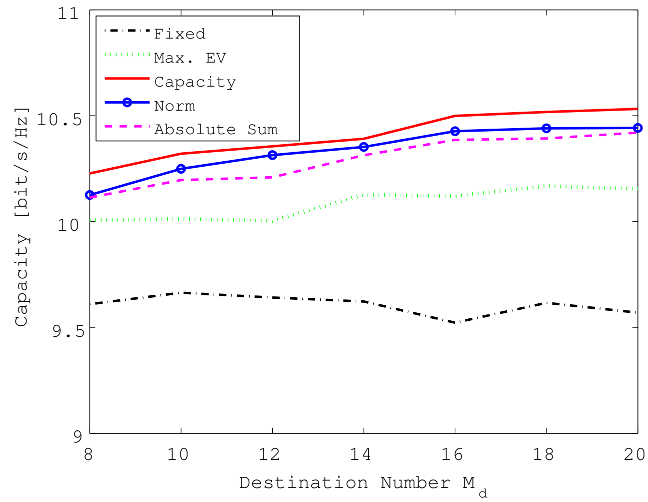


Figure 3. Destination number versus capacity in fundamental system ($L_m = 2$).

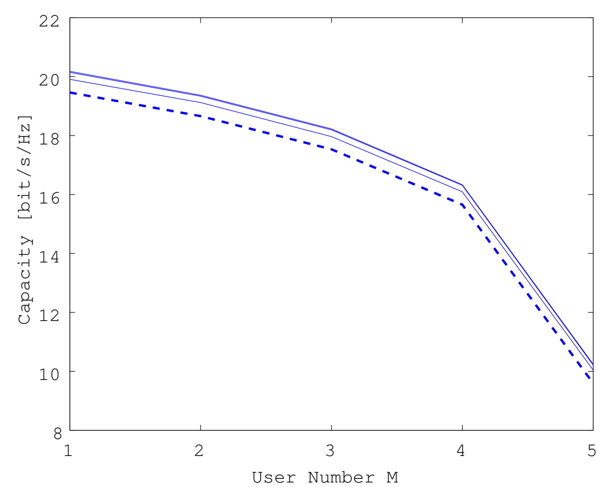


Figure 4. User number versus capacity in fundamental system ($Ns, m = 20,\ L_m = 2$).

and in (b) maximum eigenvalue) is inferior to others, but only quite small difference can be observed.

The difference among five preference functions more clearly can be seen in Figure 3, which depicts the relation between the destination number M_d versus capacity in multistream case. Though small perturbation by the randomness of the sample appears, we can observe the trend of the curves; as M_d increases, the effect of node pair selection becomes larger. From this figure, it can be seen that the performance of capacity improvement is the largest using capacity preference function, but absolute sum without multiplication attains capacity close to it, which is good nature from the viewpoint of computational cost. In this multistream case, the maximum eigenvalue is not a suitable function.

The relation between user number $M = 1 \sim 5$ and capacity (per user) is depicted in Figure 4. In this figure, every source again supports two users ($N_{d,m} = 2$), hence each of them should deal with $N_{d,m}L_m$ streams (for example, in case of $M = 5$ and $L_m = 2$,, totally 20 streams). Therefore, the number of source antenna is changed to $N_{s,m} = 20$. We can observe from the graph that the capacity decreases as the user number increase, but what is important is the effectiveness of the node pair selection is not decreased.

Turning to the target to the relay-aided system, distribution functions of capacity for fixed (broken line, preference function (a) in Section III) and node pair selection (two solid lines) adopting absolute sum preference function ((e) in Section III) are drawn in Figure 5. The latter represented by two solid curves correspond to two methods, namely, separate selection in two hops [5] and the approach shown in Section III-B. From this figure, what can be observed is they have quite similar characteristics. Therefore, in this situation, the proposed method does not have advantage against the previous one in [5] which has simpler procedure, so we need to search another application in multihop network where method [5] cannot be directly used.

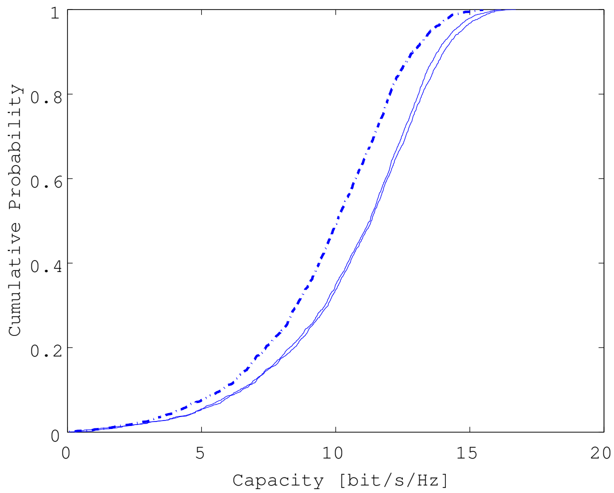


Figure 5. Distribution function of capacity in relay-aided system shown in Figure 1 (b) ($L_m = 2$).

V. CONCLUSION AND FUTURE WORK

This study has presented the extension of node pair selection scheme for multiuser MIMO communication based on stable matching problem to the case where one node can be a candidate of plural pair nodes. The repeated application of stable matching algorithm with the polynomial complexity is considered, which consists of some stages in each of which a subset of pair nodes is determined. Computer simulations have been carried out to investigate the possibility of the effectiveness of the proposed concept. The proposed method is useful for the node pair selection in multiple point system in which one source node can transact plural destinations.

A future work is the extension of the proposed method to efficient multihop rooting in multinode communication system, where the paths with different number of hops become candidates of the selection.

ACKNOWLEDGMENT

This research was supported in part by the Grant-in-Aid for Scientific Research (No. 25249056) from Japan Society for the Promotion of Science (JSPS). Authors will thank to Dr. Nobuo Nakajima, UEC, for his helpful discussion about the initial idea of this work.

REFERENCES

[1] M. Maddah-Ali, A. Motahari, and A. Khandani, "Communication over MIMO X Channels: Interference Alignment, Decomposition, and Performance Analysis," IEEE Trans. Inf. Theory, vol. 54, no. 8, Aug. 2008, pp. 3457-3470.

[2] T. Q. S. Quek, G. de la Roche, I. Gueven, and M. Kountouris (Eds)., Small Cell Networks: Deployment, PHY Techniques, and Resource Management, Cambridge University Press, Cambridge, UK, 2013.

[3] F. Monsees, C. Bockelmann, D. Wubben, and A. Dekorsy, "A sparsity aware multiuser detection for machine to machine communication," 2012 IEEE Global Commun. Conf. Workshops (Globecom Workshops), Dec. 2012.

[4] M. Barbeau and E. Kranakis, Principles of Ad-hoc Networking, Wiley, Sussex, UK, 2007.

[5] T. Taniguchi and Y. Karasawa, "An elementary study on node pair selection in relay-aided communication system based on stable marriage problem," Tech. Rep. IEICE, RCS2014-50, June. 2014.

[6] A. E. Roth and M. A. O. Sotomayor, Two-sided matching: A study in game-theoretic modeling and analysis, Cambridge University Press, Cambridge, UK, 1990.

[7] Q. H. Spencer, C. B. Peel, A. L. Swindlehurst, and M. Haardt, "An introduction to the multi-user MIMO downlink," IEEE Commun. Mag., vol. 42, no. 10, Oct. 2004, pp. 60-67.

[8] S. Loyka and G. Levin, "On outage probability and diversity-multiplexing tradeoff in MIMO relay channels," IEEE Trans. Commun., vol. 59, no. 6, pp. 1731-1741, June 2011.