JPNT 7(2), 53-59 (2018)
https://doi.org/10.11003/JPNT.2018.7.2.53

JPNT Journal of Positioning, Navigation, and Timing

A Pseudo-Random Beamforming Technique for Time-Synchronized Mobile Base Stations with GPS Signal

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ABSTRACT

This paper proposes a pseudo-random beamforming technique for time-synchronized mobile base stations (BSs) for multi-cell downlink networks which have mobility. The base stations equipped with multi-antennas and mobile stations (MSs) are time-synchronized based on global positioning system (GPS) signals and generate a number of transmit beamforming matrix candidates according to the predetermined pseudo-random pattern. In addition, MSs generate receive beamforming vectors that correspond to the beam index number based on the minimum mean square error (MMSE) using transmit beamforming vectors that make up a number of transmit beamforming matrices and wireless channel matrices from BSs estimated via the reference signals (RS). Afterward, values of received signal-to-interference-plus-noise ratio (SINR) with regard to all transmit beamforming vectors are calculated, and the resulting values are then feedbacked to the BS of the same cells along with the beam index number. Each of the BSs calculates each of the sum-rates of the transmit beamforming matrix candidates based on the feedback information and then transmits the calculated results to the BS coordinator. After this, optimum transmit beamforming matrices, which can maximize a sum-rate of the entire cells, are selected at the BS coordinator and informed to the BSs. Finally, data signals are transmitted using them. The simulation results verified that a sum-rate of the entire cells was improved as the number of transmit beamforming matrix candidates increased. It was also found that if the received SINR values and beam index numbers are feedbacked opportunistically from each of the MSs to the BSs, not only nearly the same performance in sum-rate with that of applying existing feedback techniques could be achieved but also an amount of feedback was significantly reduced.

Keywords: GPS time-synchronization, random beamforming, user scheduling, opportunistic feedback

1. INTRODUCTION

It is believed to be highly important to manage interference efficiently in order to increase communication capacity in wireless communication networks (Nam et al. 2014). Thus, a number of studies have been conducted on interference management methods using a multi-antenna-based beamforming technology. In particular, as a technology to control interference between multi-users within the cell, a technique of scheduling users and selecting an optimum transmission beamforming matrix which maximizes a sum-rate among the multi-transmit beamforming matrix candidates generated with a random method in a single cell environment, has been proposed (Choi et al. 2007). However, the technique has drawbacks that a downlink resource is wasted as a training section is needed in the downlink to select a beamforming matrix between BS and MS, and the feedback overhead with regard to multi-beamforming matrices for user scheduling increases. More recently, interference management techniques have been proposed to combine transmit-receive beamforming technique and user scheduling to improve a sum-rate by minimizing the effect of interference signals at the multi-cell environment (Jung & Shin 2011, Yang et al. 2013, 2017). However, although these technologies take the random beamforming technique into consideration, they did not consider an environment where a relatively small number of MSs are present by utilizing

Received Oct 25, 2017 **Revised** Mar 25, 2018 **Accepted** Mar 26, 2018
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http://www.ipnt.or.kr Print ISSN: 2288-8187 Online ISSN: 2289-0866

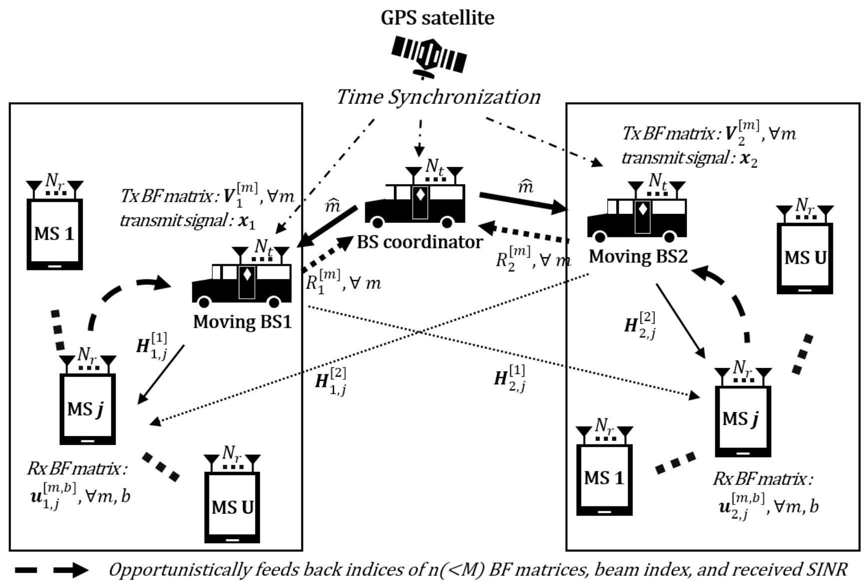

Fig. 1. The system model of a K-cell MIMO downlink cellular network.

multiple beamforming matrix candidates as presented in the aforementioned technique.

In order to use the aforementioned random beamforming techniques in a mobile BS environment, time synchronization between mobile BSs is important. In the third generation partnership project long term evolution (3GPP LTE) system that is currently commercialized, the following technologies have been used: technology that arranges uplink and downlink slots in the time domain through time synchronization between BSs or technology that reduces the interference signal effect between cells through cooperation between BSs and improves a sum-rate of MSs that exist at the cell boundaries. The time synchronization between BSs can be implemented using GPS receivers with relatively low complexity and cost (Irmer et al. 2011, Bladsjo et al. 2013).

This paper proposes a pseudo-random beamforming technique for time-synchronized mobile BSs suitable for multi-cell downlink networks which have mobility. Each of the mobile BSs generates a number of transmit beamforming matrix candidates pseudo-randomly, and MSs generate a number of receive beamforming vectors that correspond to the transmit beamforming matrix candidates based on the minimum mean square error (MMSE). In addition, the SINR values received using each of the receive beamforming vectors and the beam index numbers are feedbacked to the BSs. Each of the BSs calculates a sum-rate for each of all the transmit beamforming matrix candidates based on the collected information, thereby transmitting it to the BS coordinator. Finally, the BS coordinator selects the optimal transmit beamforming matrix candidate that can maximize a sum-rate of all cells and performs transmission using the selected candidate. Out of a number of transmit beamforming matrix candidates, the existing feedback techniques, which feedback SINR values and beam index numbers for all transmit beamforming vectors, require a large amount of feedback information. To solve this problem, an opportunistic feedback technique (Jung et al. 2007) that feedbacked only some of the receive SINR values in descending order was applied to reduce the amount of feedback information significantly. Simulation experiments verified that the nearly same performance in sum-rate can be obtained compared to that of existing feedback technique applied.

The present paper is organized as follows: In Section 2, a system model of multi-cell downlink cellular network is presented. Section 3 explains the operation procedure of the proposed pseudo-random beamforming technique for mobile BSs that are time-synchronized. In Section 4, the performance of the proposed technique is verified through computer simulations. In Section 5, conclusions are derived.

2. SYSTEM MODEL

The downlink cellular network model consisting of mobile BSs and MSs, which is studied in this paper, is described here. Fig. 1 shows an example of the downlink network where K cells exist. In the system model, mobile BSs, in which N_t antennas are held in each cell, and U MSs having N_r antennas, are present. All BSs are assumed to employ the same frequency during the downlink transmission and have been time-synchronized using GPS signals. The wireless

https://doi.org/10.11003/JPNT.2018.7.2.59

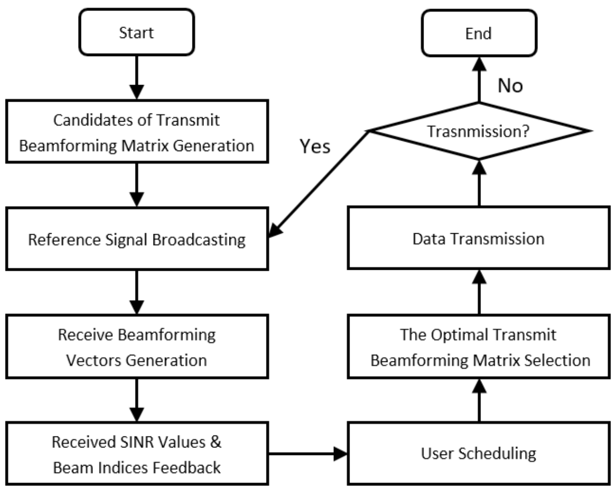

Fig. 2. Flow chart of the proposed technique.

channel matrix from the k-th BS to the j-th MS in the i-th cell is $\boldsymbol{H}_{i,j}^{[k]} \in \boldsymbol{C}^{N_r \times N_t}$. Here, it satisfies $i, k \in \{1, \ldots, K\}$ and $j \in \{1, \ldots, U\}$, and the channel is independent and identically distributed (i.i.d.) with regard to all i, j, k. Since it is quasi-static during the data signal transmission, the channel coefficient is assumed to be an unchangeable constant. However, considering the MS environment, once transmit data signals change over time, it is assumed to change independently. Assuming that M pseudo-random beamforming matrix candidates consisting of $B(\leq N_t)$ transmit beamforming vectors created using a pseudo-random method are already generated, the beam index number of the transmit beamforming matrix satisfies $m \in \{1, \ldots, M\}$ and the transmit beamforming index number satisfies $b \in \{1, \ldots, B\}$. Thus, the m-th transmit beamforming matrix candidate generated at the k-th BS satisfies $\boldsymbol{V}_k^{[m]} = [\boldsymbol{v}_k^{[m,1]}, \ldots, \boldsymbol{v}_k^{[m,b]}, \ldots, \boldsymbol{v}_k^{[m,B]}] \in \boldsymbol{C}^{N_t \times N_t}$, and the b-th transmit beamforming vector in the candidate satisfies $\boldsymbol{v}_k^{[m,b]} \in \boldsymbol{C}^{N_t \times 1}$. When the k-th BS transmits data signal vector using the m-th transmit beamforming matrix candidate among M transmit beamforming matrix candidates consisting of B transmit beamforming vectors, the receive signal vector $\boldsymbol{y}_{i,j}^{[m,d]} \in \boldsymbol{C}^{N_r \times 1}$ at the j-th MS of the i-th cell that receives the data signal via the $d \in \{1, \ldots, B\}$-th transmit beamforming vector is expressed using Eq. (1).

$$\begin{aligned} \boldsymbol{y}_{i,j}^{[m,d]} &= \left(\boldsymbol{H}_{i,j}^{[i]}\right)^T \boldsymbol{V}_i^{[m]} \boldsymbol{x}_i + \sum_{k=1,k\neq i}^{K} \left(\boldsymbol{H}_{i,j}^{[k]}\right)^T \boldsymbol{V}_k^{[m]} \boldsymbol{x}_k + \boldsymbol{z}_{i,j} \\ &= \left(\boldsymbol{H}_{i,j}^{[i]}\right)^T \boldsymbol{v}_i^{[m,d]} x_i^{[d]} + \sum_{b=1,b\neq d}^{B} \left(\boldsymbol{H}_{i,j}^{[i]}\right)^T \boldsymbol{v}_i^{[m,b]} x_i^{[b]} \\ &\quad + \sum_{k=1,k\neq i}^{K} \sum_{b=1}^{B} \left(\boldsymbol{H}_{i,j}^{[k]}\right)^T \boldsymbol{v}_k^{[m,b]} x_k^{[b]} + \boldsymbol{z}_{i,j}, \end{aligned} \quad (1)$$

Here, the data signal vector that is transmitted from the k-th BS satisfies $\boldsymbol{x}_k = \left[x_k^{[1]}, \ldots, x_k^{[B]}\right]^T \in \boldsymbol{C}^{N_t \times 1}$, and the data signal vector power is assumed to be $\boldsymbol{E}[\|\boldsymbol{x}_i\|_2^2] = P$. The thermal noise at the j-th MS of the i-th cell is $\boldsymbol{z}_{i,j} \sim CN(0, N_0 \boldsymbol{I}_{N_r})$, and each of the elements is assumed to express thermal noise per receive antenna of the MS. In addition, when the k-th BS transmits data signal vector $\boldsymbol{x}_k$ using the m-th transmit beamforming matrix, and the j-th MS of the i-th cell receives data signal $x_i^{[b]}$ via the b-th transmit beamforming vector, the effective channel vector $\boldsymbol{h}_{i,j}^{[i,m,b]} \in \boldsymbol{C}^{N_r \times 1}$ of the corresponding MS is expressed as shown in Eq. (2).

$$\boldsymbol{h}_{i,j}^{[i,m,b]} \triangleq \left(\boldsymbol{H}_{i,j}^{[i]}\right)^T \boldsymbol{v}_i^{[m,b]} \quad (2)$$

3. PROPOSED PSEUDO-RANDOM BEAMFORMING TECHNIQUE BASED ON COLLABORATION BETWEEN TIME-SYNCHRONIZED MOBILE BASE STATIONS

This section in detail describes the operation procedure of the pseudo-random beamforming technique for time-synchronized mobile BSs that can be applied to the aforementioned system model in Section 2, along with flow chart (Fig. 2). In Section 2, it was assumed that time synchronization was already done between BSs using the GPS signal, and the BSs and MSs knew the information regarding M transmit beamforming matrix candidates consisting of B transmit beamforming vectors generated via a pseudo-random method. In addition, each of the MSs within the cell that receives the RS broadcast by BSs obtains a wireless channel matrix from the BS to the MS.

3.1 Generation of Receive Beamforming Vector at the MS and Beam Information Feedback

An MS generates MB receive beamforming vectors that correspond to the transmit beamforming vectors based on the MMSE and wireless channel matrix, as presented in Eq. (3) (Ohwatari et al. 2011).

$$\boldsymbol{u}_{i,j}^{[m,b]} = \frac{\left(N_0 \boldsymbol{I}_{N_r} + \boldsymbol{R}_{i,j}^{[m,b]}\right)^{-1} \boldsymbol{h}_{i,j}^{[i,m,b]}}{\left\|\left(N_0 \boldsymbol{I}_{N_r} + \boldsymbol{R}_{i,j}^{[m,b]}\right)^{-1} \boldsymbol{h}_{i,j}^{[i,m,b]}\right\|}, \ \forall m, b \quad (3)$$

The receive beamforming vector $\boldsymbol{u}_{i,j}^{[m,b]} \in \boldsymbol{C}^{N_r \times 1}$ is generated at the j-th MS of the i-th cell, and it has a unit-norm. Here, the interference covariance matrix $\boldsymbol{R}_{i,j}^{[m,b]} \in \boldsymbol{C}^{N_r \times N_r}$ is expressed as shown in Eq. (4).

$$\boldsymbol{R}_{i,j}^{[m,b]} = \mathbb{E}\left[\boldsymbol{y}_{i,j}^{[m,b]} \left(\boldsymbol{y}_{i,j}^{[m,b]}\right)^H\right] - \boldsymbol{h}_{i,j}^{[i,m,b]} \left(\boldsymbol{h}_{i,j}^{[i,m,b]}\right)^H - N_0 \boldsymbol{I}_{N_r} \quad (4)$$

Assuming reception at the j-th MS of the i-th cell using the transmit beamforming vectors $\boldsymbol{u}_{i,j}^{[m,b]}$, MB receive SINR values with regard to the transmit beamforming vectors can be calculated using Eq. (5).

$$SINR_{i,j}^{[m,b]} = \frac{\left|\left(\boldsymbol{u}_{i,j}^{[m,b]}\right)^H \boldsymbol{h}_{i,j}^{[i,m,b]}\right|^2}{\left(\boldsymbol{u}_{i,j}^{[m,b]}\right)^H \left(N_0 \boldsymbol{I}_{N_r} + \boldsymbol{R}_{i,j}^{[m,b]}\right) \boldsymbol{u}_{i,j}^{[m,b]}}, \forall m,b \quad (5)$$

Using the same method, all MSs feedback MB receive SINR values and beam index numbers to the BSs in the same cell.

This study analyzed performance in sum-rate of the entire cell and the amount of feedback information when existing feedback and the opportunistic feedback techniques were applied. Let us assume that the number of bits required for quantizing the receive SINR values is defined as Q.

Each of the MSs feedbacks the maximum receive SINR value and a total of M corresponding transmit beamforming vector index numbers from the m-th transmit beamforming matrix candidate when existing feedback technique is applied. Thus, the number of feedback bits required per MS is expressed as shown in Eq. (6).

$$F_{conv} = M(log_2 B + Q) \quad (6)$$

When the opportunistic feedback technique proposed in this study is applied, each MS selects a maximum receive SINR value from the m-th transmit beamforming matrix candidate and a total of M corresponding transmit beamforming vector index numbers. Each MS feedbacks only the predetermined number of $n(<M)$ feedbacks in descending order of SINR values. Thus, the number of feedback bits required per MS is expressed as shown in Eq. (7).

$$F_{max-n-SINR} = n(log_2 MB + Q) \quad (7)$$

For example, assuming that the number M of transmit beamforming candidates is 16, the number B of transmit beamforming vectors that make up the transmit beamforming matrix is four, and the number Q of bits to represent the quantized SINR is six, the number F_conv of feedbacks required per MS is $16\times(log_2 4+6) = 128$ bits when applying the existing technique, whereas the number $F_{max-n-SINR}$ of feedback bits required per MS is $4\times(log_2 16\times4+6) = 48$ bits when the opportunistic feedback technique whose predetermined number n of feedbacks is four is applied.

3.2 User Scheduling at BSs

With regard to a number of transmit beamforming matrix candidates, each of the BSs selects a set of MSs whose receive SINR value is the largest during the downlink transmission using beam index numbers and receive SINR values collected from MSs that are present in the same cell. Thus, assuming that the i-th BS performs transmission using the m-th transmit beamforming matrix, an achievable sum-rate at the i-th cell can be calculated via Eq. (8).

$$R_i^{[m]} = \sum_{b=1}^{B} \left[log_2 \left(1 + \max_{1\le j\le U} SINR_{i,j}^{[m,b]} \right) \right] \quad (8)$$

BSs calculate achievable sum-rates with regard to all m and feedback $R_i^{[m]}$ through the backhole link to the BS coordinator.

3.3 Selection of Optimal Transmit Beamforming Matrix at the BS Coordinator

The BS coordinator selects the beam index number $\hat{m}$ of the optimal transmit beamforming matrix that can maximize a sum-rate of the entire cell among M transmit beamforming matrix candidates based on the achievable sum-rates collected at each cell as presented in Eq. (9) and then feedbacks it to the BSs.

$$\hat{m} = \underset{1\le m\le M}{argmax} \left[\sum_{k=1}^{K} R_k^{[m]} \right] \quad (9)$$

3.4 Data Transmission

The BSs transmit data signal vectors to the downlink using the optimal transmit beamforming matrix delivered from the BS coordinator. When the j-th MS of the i-th cell receives a data signal through the d-th transmit beamforming vector of the optimal transmit beamforming matrix, post-processing of the received signals can be done using Eq. (10).

$$\begin{aligned} \tilde{y}_{i,j}^{[\hat{m},d]} &= \left(\boldsymbol{u}_{i,j}^{[\hat{m},d]}\right)^H \boldsymbol{y}_{i,j}^{[\hat{m},d]} \\ &= \left(\boldsymbol{u}_{i,j}^{[\hat{m},d]}\right)^H \left(\boldsymbol{H}_{i,j}^{[i]}\right)^T \boldsymbol{v}_i^{[\hat{m},d]} x_i^{[d]} \\ &\quad + \left(\boldsymbol{u}_{i,j}^{[\hat{m},d]}\right)^H \textstyle\sum_{b=1,b\ne d}^{B} \left(\boldsymbol{H}_{i,j}^{[i]}\right)^T \boldsymbol{v}_i^{[\hat{m},b]} x_i^{[b]} \\ &\quad + \left(\boldsymbol{u}_{i,j}^{[\hat{m},d]}\right)^H \textstyle\sum_{k=1,k\ne i}^{K} \sum_{b=1}^{B} \left(\boldsymbol{H}_{i,j}^{[k]}\right)^T \boldsymbol{v}_k^{[\hat{m},b]} x_k^{[b]} \\ &\quad + \left(\boldsymbol{u}_{i,j}^{[\hat{m},d]}\right)^H \boldsymbol{z}_{i,j} \end{aligned} \quad (10)$$

The first term refers to a desired signal with data that should be received by the MS, the second and third terms denote the intra-cell interference signal and inter-cell interference signal. The last term means the post-processed thermal noise that follows the $CN(0, 1)$ distribution.

An achievable sum-rate of the entire cell can be calculated via Eq. (11) if the finally proposed pseudo-random beamforming technique based on cooperation between time-synchronized mobile BSs is applied to the K-cell MIMO downlink network.

$$R_{sum} = \sum_{k=1}^{K}\sum_{b=1}^{B}\left[log_2\left(1+\max_{1\le j\le U} SINR_{k,j}^{[\hat{m},b]}\right)\right] \quad (11)$$

4. SIMULATION RESULTS

This section analyzes the results of computer simulations on the proposed pseudo-random beamforming technique for time-synchronized mobile BSs, which were conducted in various system environments.

Fig. 3 shows the sum-rate per cell according to the increase in the number of MSs within the cell at an environment where three cells are present. The number of transmit antennas at each of the BSs is four, the number of receive antennas in the MS is two, the number of transmit beamforming vectors that make up the transmit beamforming matrix candidate is four, and signal-to-noise ratio (SNR) is 0 dB. The sum-rate is improved due to the similar effect of increase in the number of MSs within the cell as the number of transmit beamforming matrix candidates increases. In addition, when users feedback receive SINR values and beam index numbers, the best performance is achieved when applying the existing feedback technique. However, when the opportunistic feedback technique is applied, nearly the same sum-rate with that using the existing feedback technique can be obtained, as the number of MSs within the cell or the number of pre-determined feedbacks increases since only the predetermined number of feedbacks in descending order of receive SINR values is feedbacked.

Fig. 4 shows a sum-rate per cell when the number of antennas in the MS is four in the system parameters in Fig. 3. If the number of receive antennas in the MS increases, a receive SINR value at the MS can be improved effectively. Thus, a sum-rate per cell can be improved more rapidly if the opportunistic feedback technique is applied.

Fig. 5 shows the sum-rate per cell according to the increase in SNR at an environment where three cells are present. The number of transmit antennas at each of the BSs is four, the number of receive antennas in the MS is two, the number of transmit beamforming vectors that make up the transmit beamforming matrix candidate is four, and the number of MSs within the cell is 20. As the SNR increases, a sum-rate per cell increases. When the opportunistic feedback technique is applied, a sum-rate per cell is improved more steeply as the number of feedbacks increases.

Fig. 6 shows a sum-rate per cell when the number of antennas in the MS is four in the system parameters in Fig. 5. As the number of receive antennas in the MS increases, the receive SINR value is improved effectively at the MS. Thus, when the opportunistic feedback technique is applied, a sum-rate per cell is improved more steeply, which is similar

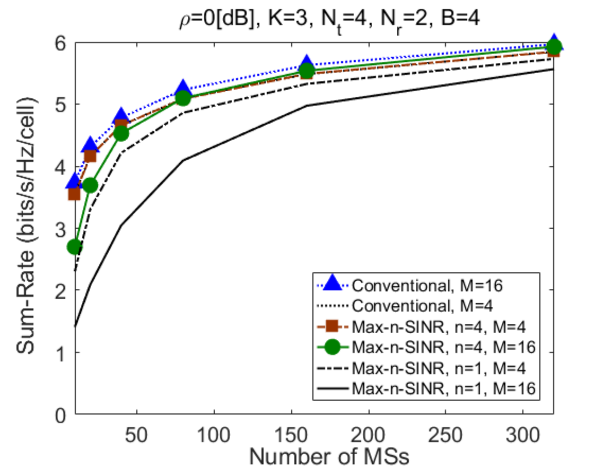

Fig. 3. Sum-rates versus the number of MSs when $K = 3$, $N_t = B = 4$ and $N_r = 2$.

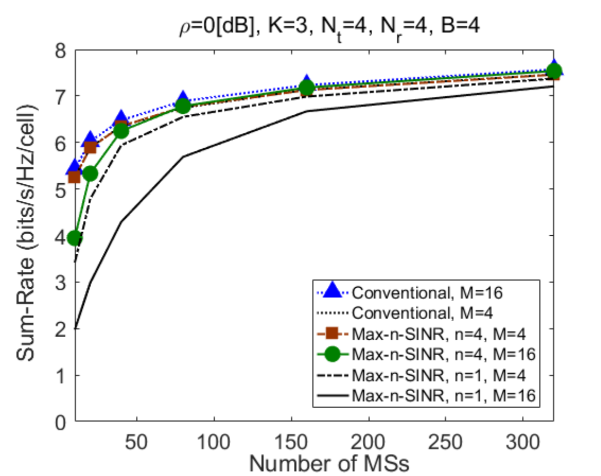

Fig. 4. Sum-rates versus the number of MSs when $K = 3$, $N_t = B = 4$ and $N_r = 4$.

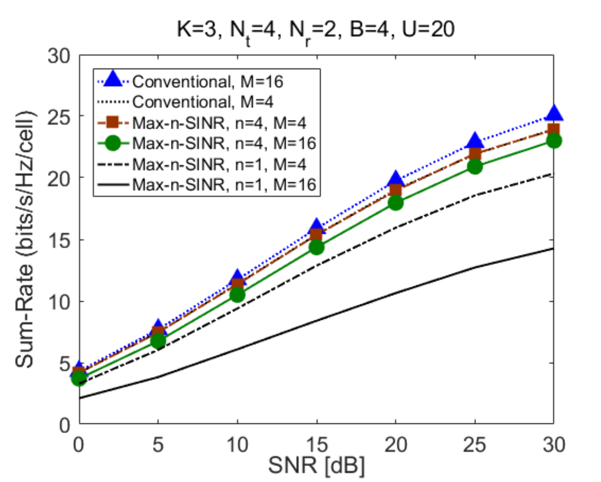

Fig. 5. Sum-rates versus SNR when $K = 3$, $N_t = B = 4$ and $N_r = 2$.

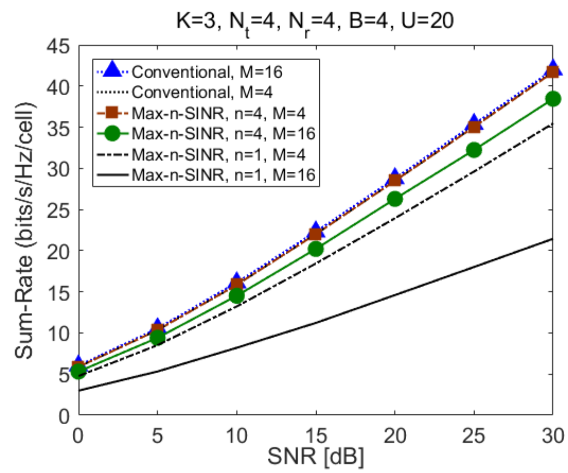

Fig. 6. Sum-rates versus SNR when $K = 3$, $N_t = B = 4$ and $N_r = 4$.

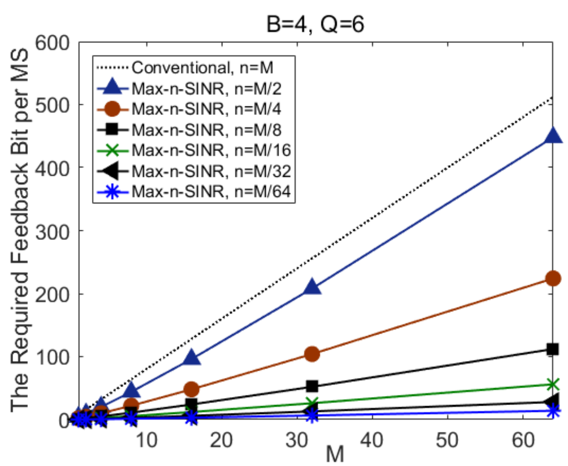

Fig. 7. Feedback overhead versus the number of transmit beamforming candidates when $B = 4$ and $Q = 6$.

to shown in the above.

Fig. 7 shows the number of feedback bits required per MS according to the number of transmit beamforming matrix candidates when the existing feedback and opportunistic feedback techniques are applied in the proposed pseudo-random beamforming technique. The number of beamforming vectors that make up the transmit beamforming matrix candidate is four, and the number of bits required to quantize the receive SINR value is six. As the number of the transmit beamforming matrix candidates increases, an increase in an amount of feedback information in the opportunistic feedback technique is relatively slowed down, compared to that of existing feedback technique.

5. CONCLUSIONS

This paper proposed the pseudo-random beamforming technique for time-synchronized mobile BSs that combined the opportunistic feedback technique, and analyzed the performance in various environments. In particular, mobile BSs that are time-synchronized using GPS signals generate a number of pseudo-random transmit beamforming matrix candidates, and MSs generate receive beamforming vectors that can maximize the receive SINR value based on MMSE in response to the transmit beamforming vectors that make up the transmit beamforming matrix. Based on the above operation results, the MSs feedback receive SINR and beam index numbers to the BSs. However, the exiting feedback technique requires a large amount of feedbacks. However, this increasing feedback amount can be reduced by applying the opportunistic feedback technique. The simulation experiment results verified the reduction in feedback information amount while maintaining a sum-rate achieved at the existing feedback technique if the opportunistic feedback was applied to the proposed technique. However, it is more effective to utilize the existing method that feedbacks the maximum SINR value with regard to all the pseudo-random beamforming matrices than using the opportunistic feedback method in an environment where a downlink data sum-rate is more important than reducing the uplink feedback overhead.

ACKNOWLEDGMENTS

This work has been supported by the National GNSS Research Center program of Defense Acquisition Program Administration and Agency for Defense Development.

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