A Near-Far Resistant Preambleless Blind Receiver with Eigenbeams Applicable to Sensor Networks

Kuniaki Yano and Yukihiro Kamiya

Abstract BRAKE has been proposed as a preambleless blind receiver (PBR) applicable to spread spectrum (SS) signals. However, the performance is degraded under the near-far problem. In this paper, we propose an eigenbeam BRAKE, i.e., the combination of BRAKE with the pre-beamforming using the eigenvectors derived from the correlation matrix. This scheme is to avoid the performance degradation under the near-far problem. Although this combination is expected to be effective, a new algorithm for controlling BRAKE is required to make it work with eigenbeams. So this paper proposes the BRAKE control algorithm as well. The performance is verified through computer simulations.

Keywords Blind signal processing · BRAKE · Eigenbeams

1 Introduction

Preambleless blind receivers (PBRs) which do not require preambles for the channel estimation and the timing detection is interesting for the implementation of the base station in wireless sensor networks. It is expected that PBRs enable sensor nodes to reduce the power consumption since the sensor nodes do not have to send the preambles. At the same time, PBRs also contribute to simplify the sensor node structures.

BRAKE was proposed in [1] as a PBR for spread spectrum signals. It blindly and concurrently achieves beamforming by using multiple antennas, RAKE combining and the timing detection based on the constant modulus algorithm (CMA) [2].

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However, the performance of BRAKE is degraded under the near-far problem. To overcome this problem, in this paper, we propose to combine BRAKE with eigenbeams (EBs) [3] which are generated by using eigenvectors of the correlation matrix.

In addition, we propose a control scheme of BRAKE which is necessary to combine with EBs as well. This scheme is required since weight matrices of BRAKE has to be adjusted depending on the situation in which the received signals are dispersed over several EBs or concentrates in an EB. None of [4–8] deals with the application of EBs over the space-domain signal processing. The performance will be verified through computer simulations.

2 Preliminaries

2.1 System Overview

Figure 1 shows the system overview in which there are U transmitters. Suppose that the u $(1 \leq u \leq U)$th transmitter sends L_{B} bits of data expressed as a vector as

$$\mathbf{b}_u = \begin{bmatrix} b_{1,u} & b_{2,u} & \cdots & b_{L_{\mathrm{B}},u} \end{bmatrix}^{\mathrm{T}} \tag{1}$$

This is modulated and we obtain L_{Q} symbols as

$$\mathbf{q}_u = \begin{bmatrix} q_{1,u} & q_{2,u} & \cdots & q_{L_{\mathrm{Q}},u} \end{bmatrix}^{\mathrm{T}} \tag{2}$$

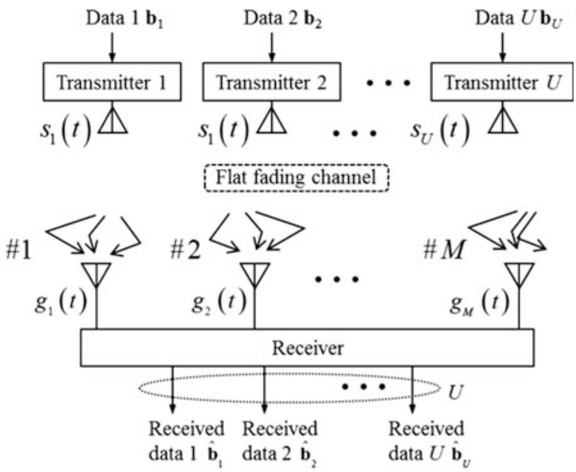

Fig. 1 System overview

The unit-power signal sent by the transmitter is formulated as follows:

$$s_u(t) = \sum_{l_Q - 1}^{L_Q} q_{l_Q,u} \sum_{l_C - 1}^{L_C} c_{l_C,u}\delta(t - (l_Q L_C + l_C)T_{CHIP}) \quad (3)$$

where $q_{l_Q,u}$ and $c_{l_C,u}$ denote the l_Qth symbol and the l_Cth chip of the spreading code, respectively. Let T_{CHIP} denote the chip duration while $\delta(t)$ is the impulse response of the band-limit filter. Finally, γ is defined as $\gamma = l_Q L_C + l_C$.

The signals go through flat fading channels and received by M antennas equipped with the receiver. The received signals are formulated as follows:

$$\mathbf{g}(t) = \mathbf{H}\mathbf{s}(t) + \sqrt{\frac{P_N}{2\mathbf{n}(t)}} \quad (4)$$

$$\mathbf{g}(t) = [\, g_1(t) \quad g_2(t) \quad \cdots \quad g_M(t) \,]^T \quad (5)$$

$$\mathbf{s}(t) = [\, s_1(t) \quad s_2(t) \quad \cdots \quad s_U(t) \,]^T \quad (6)$$

$$\mathbf{n}(t) = [\, n_1(t) \quad n_2(t) \quad \cdots \quad n_M(t) \,]^T \quad (7)$$

where $\mathbf{g}_m(t)$ is the received signal at the mth $(=1, \ldots, M)$ antenna, obtained through the RF-front ends (RF-E/Fs) while $\mathbf{n}(t)$ of size $(M \times 1)$ contains the unit-power complex AWGN. Also, P_N and $\mathbf{H}$ are the noise power and the matrix $(M \times U)$ containing the channel coefficients, respectively.

Next, the received signals are sampled as follows:

$$\mathbf{g}[k] = \mathbf{g}(kT_{SMP} + T_{OFF}) \quad (8)$$

where T_{SMP} and T_{OFF} denote the sampling duration and the timing offset, respectively, while k $(=0, 1, \ldots, K-1)$ is an integer as a timing index. The largest number of k is given by K as follows:

$$K = L_C L_Q \frac{T_{CHIP}}{T_{SMP}} \quad (9)$$

2.2 *Receiver Configuration*

Receiver Configuration Overview

Figure 2 shows the receiver configuration. The samples are fed into the eigenvector selector and beam generator (ESBG).

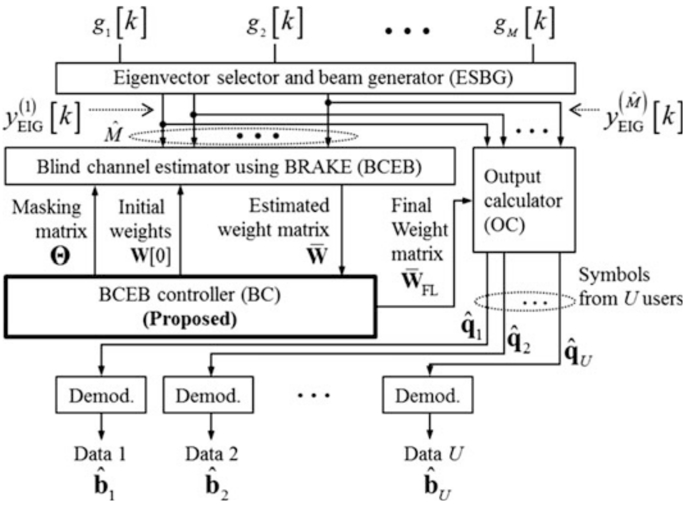

Fig. 2 Receiver configuration overview

In this part, $\widehat{M}$ beam outputs are obtained using the selected eigenvector of the correlation matrix, as explained in the next section, followed by the explanation of the blind channel estimator using BRAKE (BCEB), estimating blindly the channel coefficients and the timing using BRAKE. The control algorithm is located in the BCEB controller (BC). This is the algorithm necessary to combine the BCEB with the ESBG. It sets the initial weight matrix for BCEB, or gives constraints by the masking matrix, as explained in Sect. 3. In addition, BC decides the final weight matrix and send it to the output calculator (OC) to obtain the received symbol vectors $\hat{\mathbf{q}}_1, \hat{\mathbf{q}}_2, \ldots, \hat{\mathbf{q}}_U$ which corresponds to $\mathbf{q}_1, \mathbf{q}_2, \ldots, \mathbf{q}_U$. Finally the OC is briefly explained.

Eigenvector Selector and Beam Generator (ESBG)

By using $\mathbf{g}[k]$, the correlation matrix $\mathbf{R}$ of size $(M \times M)$ is obtained as follows:

$$\mathbf{R} = \frac{\mathbf{G}\mathbf{G}^{\mathrm{H}}}{K} \tag{10}$$

where $\mathbf{G} = [\mathbf{g}[0] \;\; \mathbf{g}[1] \;\; \cdots \;\; \mathbf{g}[K-1]]^{\mathrm{T}}$.

We obtain the eigenvectors of $\mathbf{R}$ through the eigenvalue decomposition (EVD) as follows:

$$\mathbf{R} = \mathbf{V}\mathbf{D}\mathbf{V}^{\mathrm{H}} \tag{11}$$

$$\mathbf{D} = \mathrm{diag}[\rho_1, \quad \rho_2, \quad \ldots, \quad \rho_M] \tag{12}$$

$$\rho_1 > \rho_2 > \cdots > \rho_{U+1} = \rho_{U+2} = \cdots = \rho_M = P_{\mathrm{N}} \tag{13}$$

$$\mathbf{V} = [\, \mathbf{v}_1 \quad \mathbf{v}_2 \quad \cdots \quad \mathbf{v}_M \,] \tag{14}$$

$$\mathbf{v}_m = [\, v_{1,m} \quad v_{2,m} \quad \cdots \quad v_{M,m} \,]^{\mathrm{T}} \tag{15}$$

The eigenvectors $\mathbf{v}_1, \mathbf{v}_2, \ldots, \mathbf{v}_{\widehat{M}}$ are corresponding to the $\widehat{M}$ eigenvalues selected according to the following criterion

$$\rho_1 > \rho_2 > \cdots > \rho_{\widehat{M}} \geq \beta \rho_M \tag{16}$$

where β is a constant. These are employed to generate the following signals.

$$\mathbf{y}_{\mathrm{EIG}}[k] = \widehat{\mathbf{V}}^{\mathrm{H}} \mathbf{g}[k] \tag{17}$$

$$\mathbf{y}_{\mathrm{EIG}}[k] = \left[y_{\mathrm{EIG}}^{(1)}[k] \quad y_{\mathrm{EIG}}^{(2)}[k] \quad \cdots \quad y_{\mathrm{EIG}}^{(\widehat{M})}[k] \right]^{\mathrm{T}} \tag{18}$$

$$\widehat{\mathbf{V}} = \left[\mathbf{v}_1 \quad \mathbf{v}_2 \quad \cdots \quad \mathbf{v}_{\widehat{M}} \right] \tag{19}$$

Blind Channel Estimator Using BRAKE (BCEB)

BCEB blindly estimates the channel coefficients and the timing based on BRAKE [1]. Figure 3 shows its configuration.

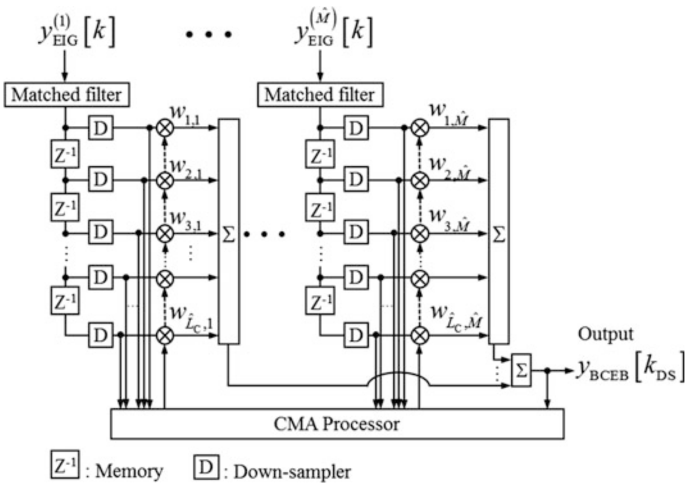

Fig. 3 BCEB configuration

The signals contained in $\mathbf{y}_{\mathrm{EIG}}[k]$ are fed into the matched filters as follows:

$$\mathbf{y}_{\mathrm{MF}}\left[\tilde{k}\right] = \sum_{\zeta=1}^{\widehat{L}_{\mathrm{C}}} \hat{c}_{\zeta}\mathbf{y}_{\mathrm{EIG}}[\tilde{k}-\zeta], \quad \tilde{k}-\zeta>0 \tag{20}$$

$$\mathbf{y}_{\mathrm{MF}}\left[\tilde{k}\right] = \begin{bmatrix} y_{\mathrm{MF}}^{(1)}\left[\tilde{k}\right] & y_{\mathrm{MF}}^{(2)}\left[\tilde{k}\right] & \cdots & y_{\mathrm{MF}}^{\left(\widehat{M}\right)}\left[\tilde{k}\right] \end{bmatrix}^{\mathrm{T}} \tag{21}$$

where $\hat{c}_{\zeta}$ is the ζth weight coefficient of the matched filter.

The variable $\hat{c}_{\zeta}$ is equal to the samples of the band-limited waveform of the spreading code $\mathbf{c}$. Let us define such weight coefficients of the matched filter as a vector $\hat{\mathbf{c}}$ of size $\left(\widehat{L}_{\mathrm{C}}\times 1\right)$ as follows:

$$\hat{\mathbf{c}} = \begin{bmatrix} \hat{c}_1 & \hat{c}_2 & \cdots & \hat{c}_{\widehat{L}_{\mathrm{C}}} \end{bmatrix}^{\mathrm{T}}, \quad \widehat{L}_{\mathrm{C}} = L_{\mathrm{C}}\frac{T_{\mathrm{CHIP}}}{T_{\mathrm{SMP}}} \tag{22}$$

In addition, $\tilde{k}=0, 1, \ldots, \tilde{K}-1$ is the timing index where $\tilde{K}$ is given as follows:

$$\tilde{K} = \widehat{L}_{\mathrm{C}}L_{\mathrm{Q}} + \left(\widehat{L}_{\mathrm{C}}-1\right) \tag{23}$$

The matched filters are followed by the tapped delay lines (TDLs) as depicted in Fig. 3. The stored samples in the TDLs are down-sampled as follows:

$$\mathbf{Y}_{\mathrm{DS}}[k_{\mathrm{DS}}] = \begin{bmatrix} \mathbf{y}_{\mathrm{MF}}\left[k_{\mathrm{DS}}\widehat{L}_{\mathrm{C}}\right] \\ \mathbf{y}_{\mathrm{MF}}\left[k_{\mathrm{DS}}\widehat{L}_{\mathrm{C}}+1\right] \\ \vdots \\ \mathbf{y}_{\mathrm{MF}}\left[k_{\mathrm{DS}}\widehat{L}_{\mathrm{C}}+\left(\widehat{L}_{\mathrm{C}}-1\right)\right] \end{bmatrix} \tag{24}$$

where $k_{\mathrm{DS}}=0, 1, \ldots, L_{\mathrm{Q}}-1$ is the down-sampling timing index.

The output of BCEB is obtained as follows:

$$y_{\mathrm{B}}[k_{\mathrm{DS}}] = \mathrm{vec}(\mathbf{W}[k_{\mathrm{DS}}])^{\mathrm{H}}\mathrm{vec}(\mathbf{Y}_{\mathrm{DS}}[k_{\mathrm{DS}}]) \tag{25}$$

where $\mathbf{W}[k_{\mathrm{DS}}]$ is a weight matrix defined as follows:

$$\mathbf{W}[k_{\mathrm{DS}}] = \begin{bmatrix} \mathbf{w}_1[k_{\mathrm{DS}}] & \mathbf{w}_2[k_{\mathrm{DS}}] & \cdots & \mathbf{w}_{\widehat{M}}[k_{\mathrm{DS}}] \end{bmatrix} \tag{26}$$

$$w_{\hat{m}}[k_{\mathrm{DS}}] = \begin{bmatrix} w_{1,\hat{m}}[k_{\mathrm{DS}}] & w_{2,\hat{m}}[k_{\mathrm{DS}}] & \cdots & w_{\widehat{L}_{\mathrm{C}},\hat{m}}[k_{\mathrm{DS}}] \end{bmatrix}^{\mathrm{T}} \tag{27}$$

where $\hat{m}=1, 2, \ldots, \widehat{M}$. The function vec(•) is to vertically vectorize a matrix, piling column-on-column manner. The weight matrix $\mathbf{W}[k_{\mathrm{DS}}]$ is recursively estimated by the following equation based on CMA criterion [1].

$$\mathbf{W}[k_{\mathrm{DS}}+1] = \mathbf{W}[k_{\mathrm{DS}}] \circ \boldsymbol{\Theta} - \nabla_{\mathbf{W}} \tag{28}$$

$$\nabla_{\mathbf{W}} = 4\mu \mathbf{Y}_{\mathrm{DS}}[k_{\mathrm{DS}}] y_{\mathrm{B}}^{*}[k_{\mathrm{DS}}] \Delta[k_{\mathrm{DS}}] \tag{29}$$

$$\Delta[k_{\mathrm{DS}}] = \left(|y_{\mathrm{B}}[k_{\mathrm{DS}}]|^2 - \sigma^2 \right) \tag{30}$$

where μ and σ are constant. The matrix $\boldsymbol{\Theta}$ whose size is identical to that of $\mathbf{W}[k_{\mathrm{DS}}]$ is called the masking matrix which will be explained in Sect. 3. The operator $\circ$ indicates the Hadamard product, i.e., the element-wize product.

Output Calculator (OC)

The OC calculates the output using the final weight matrix based on the Eq. (25). The details will be given at [Step 6] in Sect. 3.

3 Proposed Algorithm—BCEB Controller (BC)

In this chapter, we propose an algorithm necessary to combine the blind channel estimator using BRAKE (BCEB) with EBs. The algorithm will be explained as follows:

[Step 1] Setting of initial values:
Set $\psi = 1$. Set the initial weight matrix and the masking matrix as follows:

$$[\mathbf{W}[0]]_{\hat{l}_{\mathrm{C}}, \hat{m}} = \begin{cases} 1 & \text{if } \hat{l}_{\mathrm{C}} = 1 \\ 0 & \text{else} \end{cases} \tag{31}$$

In addition,

$$\boldsymbol{\Theta}|_{\mathrm{STEP1}} = \mathbf{I}\left(\widehat{L}_{\mathrm{C}} \times \widehat{M} \right) \tag{32}$$

where $\mathbf{I}(L \times M)$ denotes a matrix of size $(L \times M)$ in which all entities are 1.
[Step 2] Send $\mathbf{W}[0]$ and $\boldsymbol{\Theta}|_{\mathrm{STEP1}}$ to BCEB. So we can obtain the weight matrix after the convergence of (28). Let us call the obtained weight matrix as $\overline{\mathbf{W}}_{\psi}$.
[Step 3] Signal timing detection: Identify the entity whose amplitude is maximum as follows:

$$\left| \bar{w}_{\max}^{\psi} \right| = \max_{1 \le \hat{l}_{\mathrm{C}} \le \widehat{L}_{\mathrm{C}},\, 1 \le \hat{m} \le \widehat{M}} \left(\left| \overline{\mathbf{W}}_{\psi} \right|_{\hat{l}_{\mathrm{C}}, \hat{m}} \right) \tag{33}$$

Suppose that the maximum amplitude entity is located on $\left(\hat{l}_{\max}, \hat{m}_{\max} \right)$ in $\overline{\mathbf{W}}_{\psi}$.

[Step 4] Decision: dispersion or concentration of the signal power over the EBs. Extract the $\hat{l}_{\max}$th row of $\overline{\mathbf{W}}_{\psi}$ as follows:

$$\begin{bmatrix} \bar{w}^{(\psi)}_{\hat{l}_{\max},1} & \cdots & \bar{w}^{(\psi)}_{\hat{l}_{\max},\hat{m}_{\max}} & \cdots & \bar{w}^{(\psi)}_{\hat{l}_{\max},\widehat{M}} \end{bmatrix} \tag{34}$$

Note $\left|\bar{w}^{(\psi)}_{\max}\right| = \left|\bar{w}^{(\psi)}_{\hat{l}_{\max},\hat{m}_{\max}}\right|$. Check if there is any entity whose amplitude exceeds more than $\alpha\left|\bar{w}^{(\psi)}_{\max}\right|$ where $\alpha \le 1$, except the entity $\bar{w}^{(\psi)}_{\hat{l}_{\max},\hat{m}_{\max}}$. So we decide that the signal power is dispersed over the EBs. Then, go to Step 4-1. If not, it is decided that the signal power concentrates in the $\hat{m}_{\max}$th beam, and go to Step 4-2.
[Step 4-1] Set $\mathbf{W}[0]$ as

$$\mathbf{W}[0] = \mathbf{I}\left(\widehat{L}_{\mathrm{C}} \times \widehat{M}\right) \tag{35}$$

and the masking matrix as follows:

$$\left[\mathbf{\Theta}|_{\mathrm{STEP3}}\right]_{\hat{l}_{\mathrm{C}},\hat{m}} = \begin{cases} 1 & \text{if } \hat{l}_{\mathrm{C}} = \hat{l}^{(\max)}_{\mathrm{C}}[\psi] \pm 3 \text{ and } 1 \le \hat{m} \le \widehat{M} \\ 0 & \text{else} \end{cases} \tag{36}$$

[Step 4-2] Set $\mathbf{W}[0]$ as (35), and the masking matrix as follows:

$$\left[\mathbf{\Theta}|_{\mathrm{STEP3}}\right]_{\hat{l}_{\mathrm{C}},\hat{m}} = \begin{cases} 1 & \text{if } \hat{m} = \hat{m}_{\max}, \text{ and } 1 \le \hat{l}_{\mathrm{C}} \le \widehat{L}_{\mathrm{C}} \\ 0 & \text{else} \end{cases} \tag{37}$$

[Step 5] Send $\mathbf{W}[0]$ and $\mathbf{\Theta}|_{\mathrm{STEP3}}$ to BCEB. BCEB returns the weight matrix. Store it as $\overline{\mathbf{W}}^{(\psi)}_{\mathrm{FL}}$.
[Step 6] Output calculation: Send $\overline{\mathbf{W}}^{(\psi)}_{\mathrm{FL}}$ to OC so that we obtain the output as follows:

$$\hat{q}_{\psi}[k_{\mathrm{DS}}] = \mathrm{vec}\left(\overline{\mathbf{W}}_{\mathrm{FL}}[\psi] \circ \mathbf{\Theta}|_{\mathrm{STEP3}}\right)^{\mathrm{H}} \mathrm{vec}\left(\mathbf{Y}_{\mathrm{DS}}[k_{\mathrm{DS}}]\right) \tag{38}$$

[Step 7] If $\psi = \widehat{M}$, Finish. Otherwise, renew ψ as $\psi \leftarrow \psi + 1$ and perform (35). In addition, renew the masking matrix $\mathbf{\Theta}|_{\mathrm{STEP1}}$ as follows:

$$\mathbf{\Theta}|_{\mathrm{STEP1}} \leftarrow \mathbf{\Theta}|_{\mathrm{STEP1}} \circ \mathrm{inv}\left(\mathbf{\Theta}|_{\mathrm{STEP3}}\right) \tag{39}$$

where inv(A) denotes the function which performs the inversion of the entity of A as $1 \to 0$ or $0 \to 1$. This renewal is done to prohibit BCEB to seek the signal timing of which the signal is already detected. Back to Step 2.

4 Computer Simulations

Table 1 summarizes the simulation conditions. The parameter of CMA, namely μ defined in (30) is heuristically determined as follows: First, we set $=\mu_1 \times 10^{-\mu_2}$ $(\mu_1 \in [1,3,5,7,9]\, \mu_2 \in [11,12,13,14])$. Second, run BCEB by (28)–(30) with μ. By trying all of the μ values, we finally select the value which minimizes the following.

$$\Delta_{\text{ave}} = \frac{1}{100} \sum_{k_{\text{DS}} = L_{\text{Q}} - 100}^{L_{\text{Q}} - 1} \Delta[k_{\text{DS}}] \quad (40)$$

The simulations are performed 100 times and the output SNR is statistically evaluated in Fig. 4 which shows the output SNR versus the probability $P(\text{Output SNR[dB]} \leq \text{Abscis})$, for the signal of the lowest SNR, 0 [dB/antenna/bit], comparing the proposed method with the ideal and the compared method. In this figure, the ideal method uses the correct signal timing and the true channel coefficients. The compared method is the BRAKE without EB, i.e., the version removing BCEB and BC from the configuration shown in Fig. 2 while the final weight matrix $\overline{\mathbf{W}}_{\text{FL}}$ is directly handed to OC from BCEB. In this case, $\overline{\mathbf{W}}_{\text{FL}} = \mathbf{W}[L_{\text{Q}} - 1]$ obtained by (28).

It is clearly observed that the proposed method achieves SNR around 1 dB less than that of the ideal method at $P(\text{Output SNR[dB]} \leq \text{Abscis}) = 0.5$, even though the compared method stays at very low output SNR. It should be emphasized that the proposed method successfully detects the weakest signal even under the near-far problem.

Table 1 Simulation conditions

The number of transmitters (U)	5
Modulation	BPSK
Symbol length (L_{Q})	5000
Spreading code	127-chip M-seq.
Average SNR of each signal [dB/antenna/symbol]	0, 10, 20, 30, 40
The number of antennas (M)	20
Sampling [sample/chip]	4
Band limit filter	Cosine roll-off (roll-off factor: 0.5)
The number of weight coefficients at an antenna ($\widehat{L}_{\text{C}}$)	508 (= 127 × 4)
Constant σ in (30)	1000
Constant α in [Step 4]	0.3
Constant β in (16)	1.03

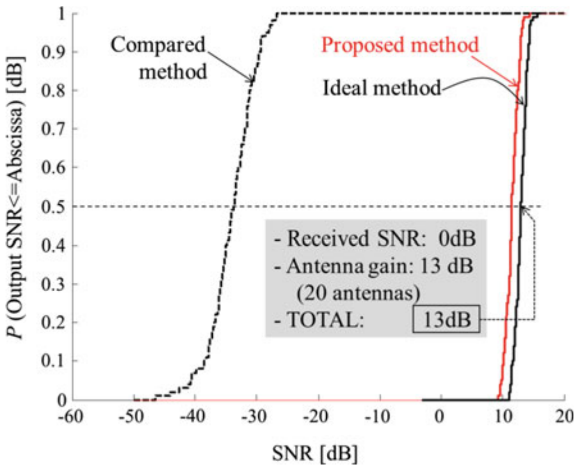

Fig. 4 Simulation result

5 Conclusions

In this paper, we proposed to combine BRAKE with EB associated with the control algorithm. Through computer simulations, we verified that the proposed method detected the weak signal even under the near-far problem.

Further considerations will apply this method to the base station of sensor networks, and will evaluate the reduction of the power consumption at the sensor nodes.

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