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Decorrelation Performance of Spatial Smoothing Preprocessing at Transmitter in the Presence of Multipath Coherent Waves

Natsumi ENDO[†], ***Student Member***, **Hiroyoshi YAMADA**[††a)], ***and*** **Yoshio YAMAGUCHI**[††], ***Members***

SUMMARY Direction of arrival estimation of coherent multipath waves by using superresolution technique often requires decorrelation preprocessings. Spatial smoothing preprocessings are the most popular schemes as the techniques. In mobile environment, position change of the target/transmitter often brings us decorrelation effect. In addition, multiple signals transmitted by an antenna array, such as a MIMO transmitter, can also cause the same effect. These effects can be categorized as the spatial smoothing preprocessing at the transmitter. In this paper, we analyze the spatial smoothing effect at the transmitter in the presence of multipath coherent waves. Theoretical and simulation results show that the spatial smoothing at the transmitter has a good feature in comparison with the conventional SSP at the receiving array. We also show that better decorrelation performance can be obtained when the SSPs at the transmitter and receiving array are applied simultaneously.

key words: *DOA estimation, decorrelation preprocessing, multipath, spatial smoothing preprocessing*

1. Introduction

Direction of Arrival (DOA) estimation is one of the important applications in the signal processing array. For the DOA estimation in indoor or urban propagation environments, we have to resolve coherent and/or highly correlated multipath waves. There are many algorithms for the DOA estimation. Superresolution techniques are the most popular algorithms among them because of their high resolution capabilities. However, subspace-based superresolution techniques, such as the MUSIC [1] or the ESPRIT [2] algorithm, cannot resolve the coherent waves directly. To overcome this difficulty, so-called Spatial Smoothing Preprocessing (SSP) [3] and/or its modified technique called Forward/Backward-SSP (FB-SSP) [4], [5] are often employed as the decorrelation preprocessing scheme. These methods utilize overlapped subarrays at the receiving array.

In this paper, we analyze the spatial smoothing effect at the transmitter, that is sources or transmitting targets to be estimated for their DOAs. For the DOA estimation of the targets in the mobile environment, the targets often move during snapshot acquisition at the receiver. In the line-of-sight propagation environment without any multiple reflections, we can easily understand that a displacement of the source is equivalent to that of the receiving array without the source displacement, which corresponds to the conventional SSP. Clearly, these problems are equivalent and bring us the same decorrelation effect. However, in the multipath environment, they are not the same. The reflected wave can be modeled by the wave from an image source. Therefore displacement-direction of the direct waves and that of the reflected waves are different.

In this paper, the decorrelation effect of displacement of the transmitter(s) in the multipath environment is analyzed, and it is shown that the preprocessing by using this effect enhances signal decorrelation performance. Hence, DOA estimation accuracy of the superresolution technique can be improved. As denoted above, this preprocessing can be considered as a spatial smoothing preprocessing at the transmitter, therefore we call the scheme as the transmitting-SSP in this paper. For simplicity, we realize the transmitting-SSP by using displacement of the transmitter/source. However, the transmitting-SSP can be also realized by using closely spaced elements, or an array, whose element transmits independent signal with each other. Therefore the preprocessing would be easily applicable to the MIMO transmitters.

In this paper we formulate the problem of DOA estimation in the multipath environment including displacement of the transmitter, and derive decorrelation performance of the proposed transmitting-SSP theoretically. Performance of the proposed scheme is verified numerically by computer simulations. The results show that the proposed scheme has several desired decorrelation characteristics; 1) The transmitting-SSP can often destroy signal correlation of closely spaced two waves effectively though the conventional SSP at the receiver cannot work well for the waves. 2) Decorrelation performance enhancement can be obtained when we apply the transmitting-SSP and the conventional SSP simultaneously. DOA estimation results of the MUSIC algorithm with each decorrelation scheme are also provided to show the availability of the proposed scheme. Performance of the proposed scheme also depends on displacement directions of the source/transmitter itself and their image source, as well as the DOAs. The concept for the decorrelation based on the image theory can be also found in the delay estimation by using swept frequency data [6].

When the proposed transmitting-SSP can destroy the signal coherence properly, we do not have to apply the conventional SSP at the receiver. This means that an array with arbitrary geometry at the receiver can be employed, and detect L-1 waves can be detected with an L-element array. This is also one of the advantages of the transmitting-SSP

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†The author is with the Graduate School of Science & Technology, Niigata University, Niigata-shi, 950-2181 Japan.

††The authors are with the Faculty of Engineering, Niigata University, Niigata-shi, 950-2181 Japan.

a) E-mail: yamada@ie.niigata-u.ac.jp

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scheme.

2. Problem Formulation

The DOA estimation environment considered in this paper is shown in Fig. 1. For simplicity, the number of the sources/transmitters is assumed to be 1. An L-element uniform linear array (ULA) with element spacing of Δx is employed in this analysis.

As shown in Fig. 1, it is assumed that there is a wall whose reflection coefficient is γ near the transmitter, thus the array receives the direct wave from the transmitter, $Tx_1^{(1)}$, and its reflected wave by the wall. The direct and reflected waves are completely correlated, or coherent.

According to the image theory, the reflected wave of $Tx_1^{(1)}$ can be modeled as the wave transmitted by the image source, $Tx_2^{(1)}$ as shown in Fig. 1. Here, we also add $Tx_1^{(i)}, Tx_2^{(i)}, i = 1, 2, \cdots, M_{tr}$, in the figure to consider the effect of displacement of the transmitter. Angles, ψ_1 and ψ_2, are the direction of the source displacements, and Δd is the separation between $Tx_j^{(i)}$ and $Tx_j^{(i+1)}$. ξ is angle of the wall surface, where $\xi = 0$ means that the wall surface is directed parallel to the broadside direction of the receiving array.

The received signal corresponding to each waves at the reference element of the receiving array (Rx_1) can be given by

$$s_1'(t) = \frac{k}{d_1} s(t - \tau_1) e^{-j2\pi \frac{d_1}{\lambda}}, \tag{1a}$$

$$s_2'(t) = \gamma \frac{k}{d_2} s(t - \tau_2) e^{-j2\pi \frac{d_2}{\lambda}}, \tag{1b}$$

where $s(t)$ is the transmitting signal of $Tx_1^{(1)}$, λ denotes wave length, and d_1 is distance between the transmitter and the reference element of the receiving array. d_2 is the propagation distance of the reflected wave. τ_i, and k are the delay time of the i-th wave and an arbitrary coefficient, respectively. It is also assumed that the source/transmitter is located in the far-field region. With these assumptions, the received data vector of the array can be written by

$$\boldsymbol{r}(t) = \boldsymbol{A}\boldsymbol{s}'(t) + \boldsymbol{n}(t), \tag{2}$$

where

$$\boldsymbol{r}(t) = [r_1(t), \cdots, r_L(t)]^T, \tag{3}$$

$$\boldsymbol{A} = [\boldsymbol{a}(\theta_1), \boldsymbol{a}(\theta_2)], \tag{4}$$

$$\boldsymbol{a}(\theta_i) = [1, e^{-j2\pi \frac{\Delta x}{\lambda} \sin\theta_i}, \cdots, e^{-j2\pi \frac{(L-1)\Delta x}{\lambda} \sin\theta_i}]^T, \tag{5}$$

$$\boldsymbol{s}'(t) = [s_1'(t), s_2'(t)]^T, \tag{6}$$

$$\boldsymbol{n}(t) = [n_1(t), \cdots, n_L(t)]^T, \tag{7}$$

The angles, θ_1 and θ_2, denote the DOA of the direct and the reflect wave, respectively. $n_i(t)$ is the additive white Gaussian noise having power of σ^2, and ^{T} denotes the transpose.

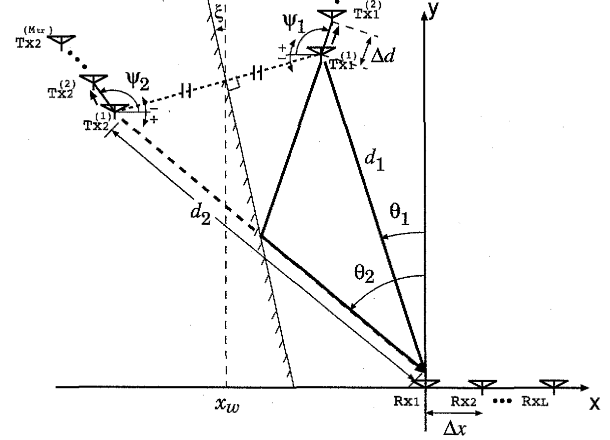


Fig. 1 Antenna layout and multipath signal model.

3. Spatial Smoothing Preprocessing at the Transmitter

3.1 Effective Correlation Coefficient of the Proposed Scheme (Transmitting-SSP)

The proposed transmitting-SSP is the decorrelation preprocessing scheme by using displacement of the transmitter. As denoted in the introduction, closely spaced sources that transmit independent signal with each other can obtain almost the same effect. Since we assume that the source exists in the far-field, the DOAs of the sources including the image source can be assumed to be unchanged by the displacement of the transmitter when the displacement is small. Here, the direct waves from $Tx_1^{(1)}$ and $Tx_1^{(2)}$ are denoted by $s_1^{(1)}(t)$ and $s_1^{(2)}(t)$, respectively. In this case, these waves have the property of $E[s_1^{(1)}(t)s_1^{(2)*}(t)] = 0$ when we have enough snapshot data at each position. This is the simplest model of the transmitting SSP, however the model can be easily extended to M_{tr} sources.

The proposed transmitting-SSP is defined by the average among the correlation matrices of the data vector at the receiver for these M_{tr} transmitting signals, $s_1^{(m)}(t), m = 1 \sim M_{tr}$. If the received data contain a multipath wave of the transmitter, we can obtain decorrelation effect by this averaging scheme. The received data vector for the transmitter $Tx_1^{(i)}, i = 1, 2, \cdots, M_{tr}$, is given by

$$\boldsymbol{r}_{tr,m}(t) = \boldsymbol{A}_{tr,1}\boldsymbol{D}_{tr}^{(m-1)}\boldsymbol{s}'(t) + \boldsymbol{n}_m(t), \quad m = 1, 2 \cdots, M_{tr}, \tag{8}$$

where

$$\boldsymbol{D}_{tr} = \begin{bmatrix} e^{-j2\pi \frac{\Delta d \sin(\theta_1 + \psi)}{\lambda}} & 0 \\ 0 & e^{j2\pi \frac{\Delta d \sin(\theta_2 - (\psi + 2\xi))}{\lambda}} \end{bmatrix}. \tag{9}$$

The preprocessed data correlation matrix $\overline{\boldsymbol{R}}_{tr}$ by the proposed scheme and the signal correlation matrix $\overline{\boldsymbol{S}}_{tr}$, can be written by

$$\overline{R}_{tr} = \frac{1}{M_{tr}}\sum_{m=1}^{M_{tr}} R_m = \frac{1}{M_{tr}}\sum_{m=1}^{M_{tr}} E[r_{tr,m} r_{tr,m}^H]$$
$$= A_{tr1}\overline{S}_{tr}A_{tr1}^H + \sigma^2 I, \quad (10)$$
$$\overline{S}_{tr} = \frac{1}{M_{tr}}\sum_{m=1}^{M_{tr}}\{D_{tr}^{m-1}S(D_{tr}^{m-1})^H\}$$
$$= \begin{bmatrix} |s_1'|^2 & \rho_{tr}s_1's_2'^* \\ \rho_{tr}^* s_1'^* s_2' & |s_2'|^2 \end{bmatrix}, \quad (11)$$

where $E[\cdot]$ denotes the ensemble averaging, and ρ_{tr} is the effective correlation coefficient. The effective correlation coefficient, ρ_{tr}, by the proposed transmitting-SSP can be derived by

$$\rho_{tr} = \frac{\sin(M_{tr}u_{tr})}{M_{tr}\sin u_{tr}} e^{-j(M_{tr}-1)u_{tr}}, \quad (12a)$$
$$u_{tr} = \pi\frac{\Delta d}{\lambda}\{\sin(\theta_1+\psi)+\sin(\theta_2-(\psi+2\xi))\}, \quad (12b)$$

where we use the property $\psi = \psi_1 = -\psi_2$.

3.2 Effective Correlation Coefficient of the Combined Scheme

The conventional SSP (at the receiving array) is a well-known decorrelation preprocessing scheme for ULAs. This SSP is defined by the averaged data correlation matrix of the overlapping subarrays. We call this preprocessing receiving-SSP in the following discussion.

The proposed transmitting-SSP and receiving-SSP are the independent preprocessing, therefore we can apply these preprocessings simultaneously. Effect of the combined preprocessing can be derived easily.

The effective correlation coefficient ρ_{re} between the direct wave and reflected wave, impinging from θ_1 and θ_2, respectively, by the receiving-SSP[3], is given by

$$\rho_{re} = \frac{\sin(Mu)}{M\sin u} e^{-j(M-1)u}, \quad (13a)$$
$$u = \pi\frac{\Delta x}{\lambda}(\sin\theta_1 - \sin\theta_2), \quad (13b)$$

where M is number of the subarrays.

As shown here, only DOAs of the incident waves are the parameters which relate to the effective correlation coefficient. DOAs of the incident waves are assumed to be unchanged by the transmitting-SSP, hence the effective decorrelation coefficient by the combined scheme, ρ, can be easily derived by $\rho = \rho_{re}\rho_{tr}$.

Consequently, the signal correlation matrix $\overline{S}$ obtained by the combined scheme can be given by

$$\overline{S} = \begin{bmatrix} |s_1'|^2 & \rho s_1's_2'^* \\ \rho^* s_1'^* s_2' & |s_2'|^2 \end{bmatrix}$$
$$= \begin{bmatrix} |s_1'|^2 & \rho_{re}\rho_{tr}s_1's_2'^* \\ \rho_{re}^*\rho_{tr}^* s_1'^* s_2' & |s_2'|^2 \end{bmatrix}. \quad (14)$$

This means that we can enhance the signal decorrelation effect by this combined scheme. The combined scheme is denoted by "transmitting/receiving-SSP" in the next section. Similarly, we can also apply the forward/backward averaging [4], [5] in addition to the combined scheme [7].

4. Numerical Study of the Proposed Schemes

4.1 Comparative Study of the Decorrelation Effect

The magnitude of the effective correlation coefficient by each preprocessing scheme for various DOAs of two coherent waves are shown in Figs. 2 and 3. Figures 2 and 3 show an example of the magnitude of the effective correlation coefficients obtained by the proposed transmitting-SSP and receiving-SSP, respectively. In these figures, the wall surface is directed to broadside direction of the receiving array ($\xi = 0$), and the element separation of the receiving array (Δx) is 0.5λ. The displacement of the transmitter (Δd) is also 0.5λ whose direction (ψ_1) is 0 degree. The hatched

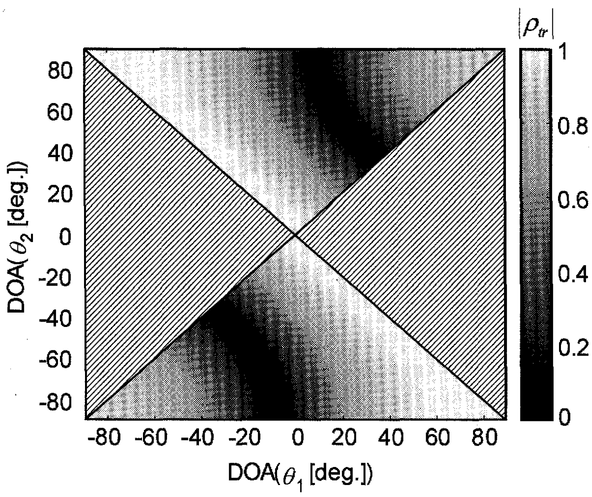


Fig. 2 Magnitude of the effective correlation coefficient of the transmitting-SSP. $\Delta x = \Delta d = \frac{\lambda}{2}$, $\psi_1 = -\psi_2 = 0$, $\xi = 0$.

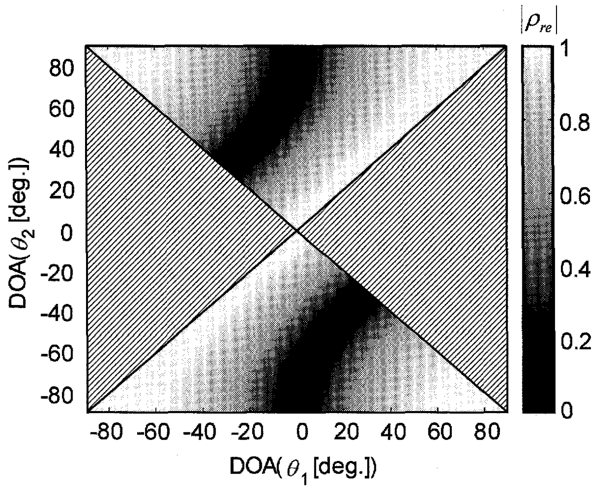


Fig. 3 Magnitude of the effective correlation coefficient of the receiving-SSP. $\Delta x = \frac{\lambda}{2}$, $\xi = 0$.

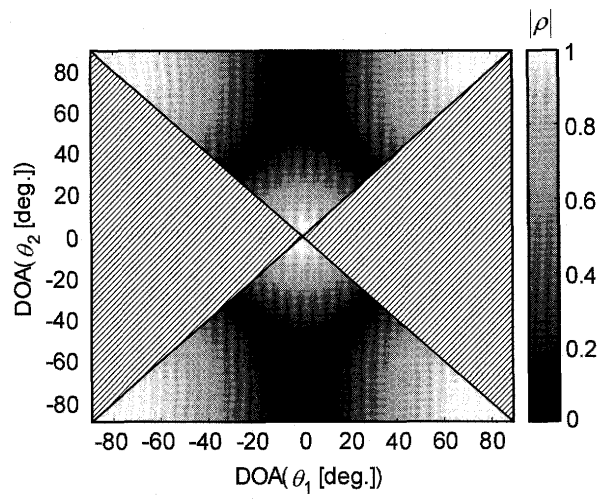


Fig. 4 Magnitude of the effective correlation coefficient of the transmitting/receiving-SSP. $\Delta x = \Delta d = \frac{\lambda}{2}, \psi_1 = -\psi_2 = 0, \xi = 0$.

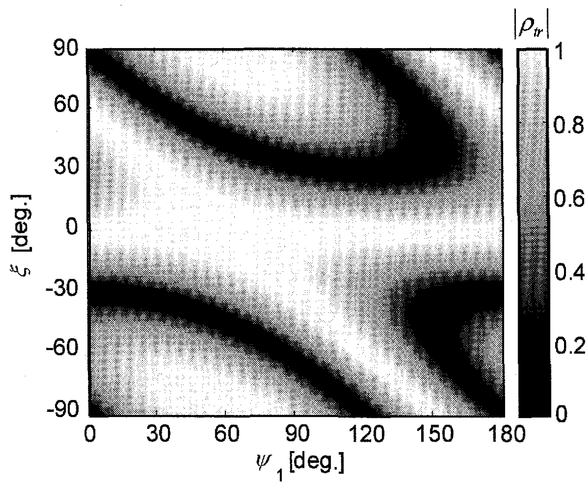


Fig. 5 Magnitude of the effective correlation coefficient in various directions of the wall and transmitter-displacement by the transmitting-SSP. $\theta_1 = 30°, \theta_2 = -30°, \Delta x = \Delta d = \frac{\lambda}{2}, \psi_1 = -\psi_2$.

parts in these figures are the area where $\tau_1 \geq \tau_2$. We assume that the wave coming from θ_1 with time-delay of τ_1 is the direct wave, then the waves should hold $\tau_1 < \tau_2$.

As shown in Fig. 3, the decorrelation effect of the receiving-SSP is relative small for the closely spaced incident waves, that is $|\rho_{re}| \simeq 1$ for the waves having $\theta_1 \simeq \theta_2$. In such a case, we can hardly obtain the high-resolution property of the MUSIC algorithm since the incident waves are still almost coherent or highly correlated. As shown in (13a), the decorrelation performance of the receiving-SSP almost depends on the angle-difference ($|\sin\theta_1 - \sin\theta_2|$). To realize high-resolution DOA estimation, the area where DOAs of the waves are closely spaced is important.

On the other hand, the magnitude of the effective correlation coefficient of the proposed transmitting-SSP can be small even when the angle-difference is small, except for the broadside and endfire direction of the receiving array ($\theta_1 \simeq \theta_2 \simeq 0°, \simeq 90°$) in the example shown in Fig. 2. Note that the decorrelation performance of the transmitting-SSP depends not only on the displacement of the transmitting antenna, but also on the displacement direction ψ and the wall direction ξ as shown in (12a). The proposed scheme cannot work effectively where $\theta_1 \simeq -\theta_2$ in this example.

Magnitude of the correlation coefficients for the transmitting/receiving-SSP for various θ_1 and θ_2 are shown in Fig. 4. The magnitudes shown in this figure corresponds to those of Fig. 3 multiplied by those of Fig. 2. Therefore this method brings us enhanced decorrelation effect than that of the transmitting or receiving-SSP alone. Disadvantages in each preprocessing can be recovered by the combined preprocessing.

4.2 Characteristic of Decorrelation for Transmitting-SSP

As we mentioned in (12a) and (12b), the decorrelation performance of the transmitting-SSP also depends on displacement direction of the transmitter and wall surface direction in addition to the DOAs of the waves. The effective correlation coefficients in various ξ and ψ_1 are shown in Fig. 5. In this figure, the direction of the direct wave is $\theta_1 = 30°$, and the DOA of the reflected wave is $\theta_2 = -30°$. The vertical and horizontal axises in the figure show the directions of the wall (ξ) and the transmitter displacement (ψ_1), respectively. The point $(\psi_1, \xi) = (0, 0)$ in Fig. 5 corresponds the point of $(\theta_1, \theta_2) = (30°, -30°)$ whose correlation coefficient is almost 1 in Fig. 2. Therefore when the direction of the target displacement(s) is known apriori, we can select the proper ξ, which is equivalent to charge broadside direction of the receiving array to obtain the best performance of the transmitting SSP.

5. Simulation Results

5.1 DOA Estimation by the Root-MUSIC Algorithm

In this section, we provide the DOA estimation results of coherent 2 waves by using the Root-MUSIC algorithm [8] with each decorrelation preprocessing. In the simulations, we select the antenna layout and multipath waves as shown in Fig. 1. The 4-element ULA ($L = 4$) with the element spacing of $\Delta x = 0.5\lambda$, where $\lambda = 12.5$ cm (frequency f=2.4 GHz), is employed. The displacement of the transmitting antenna for the transmitting-SSP is $\Delta d = \frac{\lambda}{2}$, and its direction is $-x$ ($\psi_1 = 0$). Also, it is assumed that the wall which has the reflection coefficient of $\gamma = -1$ is located parallel to the y-axis ($\xi = 0$). The distance d_1 in Fig. 1 is selected as 25 m. The number of the snapshots for the receiving-SSP is 100, and SNR of each wave is 20 dB. When we apply the transmitting-SSP, we should obtain several snapshots at the each transmitter position. In this simulation, we assume that we can obtain 100 snapshots at each transmitter position in the transmitting-SSP.

The DOA estimation error is evaluated by the RMSE (Root Mean Squared Error) and detection probability. The RMSE in this evaluation is defined by

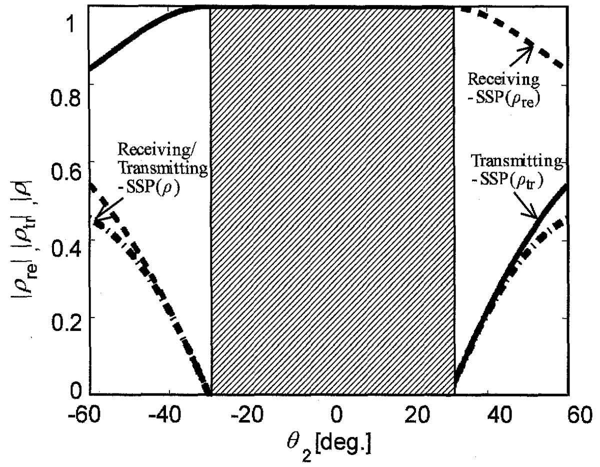


Fig. 6 Magnitude of the effective correlation coefficient by variation of reflected waves DOA. $\theta_1 = 30°$, $\Delta x = \Delta d = \frac{\lambda}{2}$, $\psi_1 = -\psi_2 = 0$, $\xi = 0$.

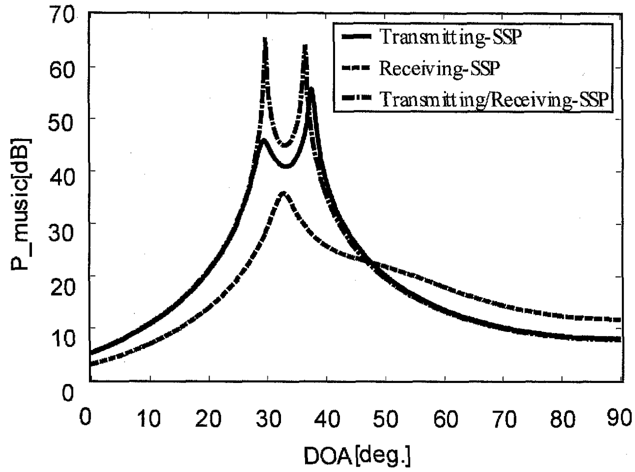
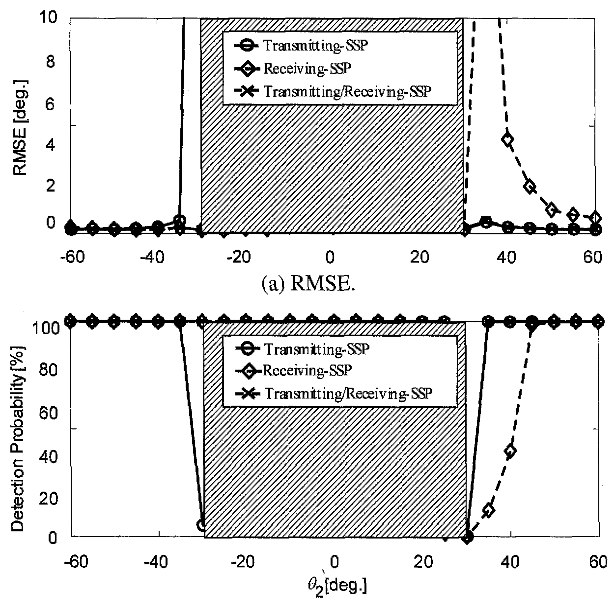


Fig. 7 MUSIC spectrum. $\theta_1 = 30°$, $\theta_2 = 37°$, $\Delta x = \Delta d = \frac{\lambda}{2}$, $\psi_1 = -\psi_2 = 0$, $\xi = 0$, $d_1 = 25$ m.



(a) RMSE.

(b) Detection capability.

Fig. 8 RMSE and detection probability of estimated DOA by variation of reflected waves DOA ($\theta_1 = 30°$, $\theta_2 = 37°$, $\Delta x = \Delta d = \frac{\lambda}{2}$, $\psi_1 = -\psi_2 = 0$, $\xi = 0$, $d_1 = 25$ m).

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\frac{(\hat{\theta}_{1,i} - \theta_1)^2 + (\hat{\theta}_{2,i} - \theta_2)^2}{2}}, \qquad (15)$$

where N denotes the number of trials, and $\hat{\theta}_{l,i}$ denotes the estimated DOA of the lth wave at the ith trial. In the simulations, the DOA of the direct wave (θ_1) and its distance (d_1) hold on 30° and 25 m, respectively. The DOA of the reflected wave is varied by the location of the wall (x_w in Fig. 1). The number of the trials is $N = 1000$. In these situation setup, the maximum variation of θ_1 by the transmitter displacement was only 0.14°, that is negligibly small. Also, the target is located in the far-filed region, hence the difference of the attenuation at each element of the receiving array can be omitted.

5.2 DOA Estimation Results

The theoretical values of the magnitude of effective correlation coefficients by each preprocessing are plotted in Fig. 6. Figure 7 show examples of the DOA estimation for the waves having $\theta_1 = 30°$ and $\theta_2 = 37°$ by the MUSIC algorithm [1] with each preprocessing. Since the effective signal correlation between the waves by the receiving-SSP is still high, as shown in Fig. 6, we cannot resolve the DOAs by the conventional scheme. When the transmitting-SSP is applied, we can almost resolve these two waves. The MUSIC spectrum can be further improved when we employ the combined preprocessing (transmitting/receiving-SSP). From there results, we can say that the transmitting-SSP is available for DOA estimation to enhance the decorrelation effect in coherent multipath environment.

The RMSE of the DOA estimation results and the detection probability by the Root-MUSIC algorithm with each scheme in various θ_2 are shown in Figs. 8(a) and 8(b), respectively. The hatched area is the area where we cannot carry out the estimation because we assume $\tau_2 < \tau_1$ in this setup. As shown in these figures, the RMSE is large and detection probability becomes low at the angles where the effective correlation coefficient is still high. In this simulation, the algorithm with the transmitting-SSP can work properly to resolve the waves having DOAs of $\theta_2 \simeq \theta_1$ ($\theta_2 \neq \theta_1$), that is closely spaced two waves, while the method cannot resolve the DOAs those having DOAs of $\theta_2 \simeq -\theta_1$. On contrary, the algorithm with the receiving-SSP cannot work well for the waves having $\theta_2 \simeq \theta_1$ ($\theta_2 \neq \theta_1$), and can work properly for the waves of $\theta_2 \simeq -\theta_1$. From these results, it can be said that the combined method, the Root-MUSIC algorithm with the transmitting/receiving-SSP, can resolve these DOAs in almost all angles except for extremely closed DOAs ($\theta_1 = \theta_2$).

6. Conclusions

In this paper, we have proposed the transmitting-SSP scheme as a correlation suppression method and analyzed its performance theoretically. The transmitting-SSP can be realized by using moving targets/transmitter during snapshot acquisition and/or closely spaced transmitters which transmit independent signals. The decorrelation performance of the proposed scheme is also verified theoretically and numerically. In addition, availability of the scheme for the MUSIC algorithm is also demonstrated by the computer simulations. From these results, it can be said that the proposed scheme can often recover the difficulty of the conventional SSP at the receiving array and achieve the superior decorrelation performance. Although the decorrelation effect by the transmitting-SSP is varied by the direction of the wall and transmitter displacement, the decorrelation performance can be enhanced when we apply the "transmitting-SSP" scheme and the conventional scheme simultaneously. Further decorrelation performance can be also obtained by the forward/backward averaging in addition to the combined scheme. Analysis of the decorrelation performance by the proposed scheme in various multipath environments still remains to be solved. This will be done in near future.

References

[1] R.O. Schmidt, "Multiple emitter location and signal parameter estimation," IEEE Trans. Antennas Propag., vol.AP-34, no.3, pp.276–280, March 1986.

[2] R. Roy, A. Paulraj, and T. Kailath, "ESPRIT-estimation of signal parameters via rotational invariance techniques," IEEE Trans. Acoust. Speech Signal Process., vol.37, no.7, pp.984–995, July 1989.

[3] T.J. Shan, M. Wax, and T. Kailath, "On spatial smoothing for direction-of-arrival estimation of coherent signals," IEEE Trans. Acoust. Speech Signal Process., vol.ASSP-33, no.4, pp.806–811, Aug. 1985.

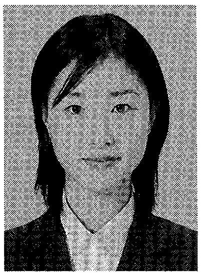
[4] R.T. Williams, S. Prasad, A.K. Mahalanabis, and L.H. Sibul, "An improved spatial smoothing technique for bearing estimation in a multipath environment," IEEE Trans. Acoust. Speech Signal Process., vol.36, no.4, pp.435–432, April 1988.

[5] S.U. Pillai and B.H. Kwon, "Forward/backward spatial smoothing techniques for coherent signal identification," IEEE Trans. Acoust. Speech Signal Process., vol.37, no.1, pp.8–15, Jan. 1989.

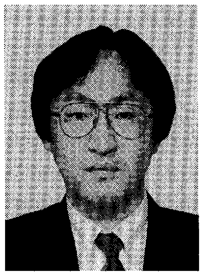
[6] F. Watano, "DOA estimation of correlated waves utilizing image waves," IEICE Trans. Commun. (Japanese Edition), vol.J85-B, no.6, pp.922–931, June 2002.

[7] N. Endo, H. Yamada, and Y. Yamaguchi, "DOA estimation of coherent waves by using spatial smoothing preprocessings in transmitter," Proc. International Symposium on Antennas and Propagation 2006, CD-ROM, Nov. 2006.

[8] B. Rao and K. Hari, "Performance analysis of root-music," IEEE Trans. Acoust. Speech Signal Process., vol.37, no.12, pp.1939–1949, Dec. 1989.



Natsumi Endo received a B.E. degree in information engineering from Niigata University, Niigata, Japan, in 2006. She is now a graduate student pursuing an M.E. degree in Mathematics, Electronics and Information Engineering at Niigata University, where she is researching and developing high-resolution DOA estimation techniques and array calibration technique.



Hiroyoshi Yamada received the B.E, M.E. and Dr.Eng. degrees in electronic engineering from Hokkaido University, Sapporo, Japan, in 1988, 1990 and 1993, respectively. In 1993, he joined the Faculty of Engineering, Niigata University, where he is an associate professor. From 2000 to 2001, he was a Visiting Scientist at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena. His current interests include superresolution techniques, array signal processing, and microwave remote sensing and imaging. Dr. Yamada is a member of the IEEE.

Yoshio Yamaguchi received a B.E. degree in electronics engineering from Niigata University in 1976 and M.E. and Dr. Eng. degrees from the Tokyo Institute of Technology in 1978 and 1983, respectively. In 1978, he joined the Faculty of Engineering, Niigata University, where he is a professor. During 1988 and 1989, he was a research associate at the University of Illinois, Chicago. His interests include the propagation characteristics of electromagnetic waves in a lossy medium, radar polarimetry, and microwave remote sensing and imaging. Dr. Yamaguchi is a fellow of the IEEE.