Proceedings of ISAP2012, Nagoya, Japan

A Switching Order Optimization for an Adaptive Array with a Single Receiver Using Time-Division Multiplexing

Ken-ichi Koga [1,2], Nobuyoshi Kikuma [2], Hiroshi Hirayama [2], Kunio Sakakibara [2]
Tatsuya Koike [1], Hiroaki Iwashita [1], Yoshiyuki Mizuno [1]
[1] R&D Center, Tokai Rika Co., Ltd.
Oguchi-cho, Niwa-gun, Aichi-ken, 480-0195 Japan, kenichi.koga@exc.tokai-rika.co.jp
[2] Department of Computer Science and Engineering, Nagoya Institute of Technology
Gokiso-cho, Showa-ku, Nagoya-shi, Aichi-ken, 466-8555 Japan,

1. Introduction

A conventional adaptive array antenna system needs the analog circuits, constructed of the filter, amplifier, down converter, AD converter, etc., for each antenna. Accordingly, it is a problem that the scale of the analog circuits for the conventional adaptive array antenna system is larger than the one for the single antenna system.

To solve this problem, the method of switching the antennas for common use of the analog circuits was introduced by Moriyama *et al.* [1]. In [1], however, the method was discussed only in the case that the time of the switch connecting the antennas with the analog circuits is very short. The short switch-on time causes the degradation of SNR (Signal-to-Noise Ratio). Therefore, we proposed the method for improving SNR with the longer switch-on time in the past study [2]. Moreover, we produced the method for further enhancing SNR with the switching order optimization [3]. Nevertheless, this method was inspected in the condition of the receiving signals from some particular directions.

In this paper, the method of the switching order optimization in the situation of the receiving signal from all possible directions is examined. Via computer simulation, it is confirmed that the switching order optimization is effective in our system.

2. Formulation

The adaptive array antenna with the single receiver using time-division multiplexing (TDM-AAA) switches the antennas for common use of the analog circuit. In Fig.1, the configuration of the TDM-AAA in this paper is shown. This TDM-AAA is composed of the single circuit except RFBPF1 (Radio Frequency Band Pass Filter 1) for each antenna.

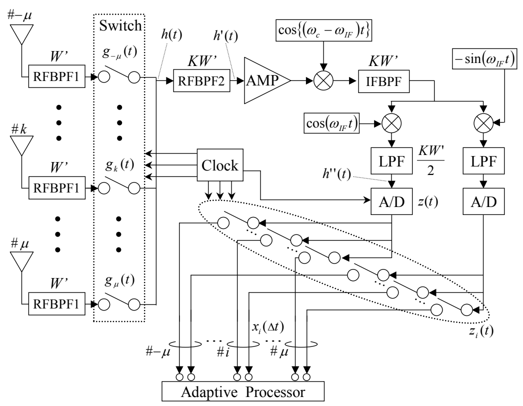

Figure 1: Configuration of single receiver using time-division multiplexing.

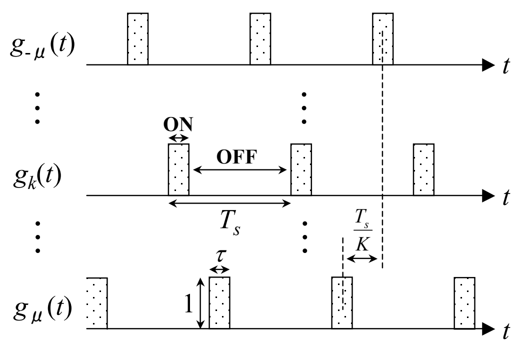

Figure 2: Time-domain waveform of switch control.

Consider the TDM-AAA with K elements. Let $f_k(t)$ denote the received baseband signal on element k ($k = -\mu, -\mu+1, -\mu+2, \cdots, \mu; \mu \equiv \frac{K-1}{2}$), and also $g_k(t)$ the switch control signal which switches the antennas with connect time τ, cycle time T_s, in Fig.2. Then, $\mathbf{X}(\Delta t)$, which is the received signal vector of the TDM-AAA, is formulated as follows [3] :

$$
\begin{aligned}
\mathbf{X}(\Delta t) &= \Phi^{-1} V \mathbf{F}(\Delta t) && (1)\\
\mathbf{X}(\Delta t) &\equiv \left[x_{-\mu}(\Delta t), \cdots, x_i(\Delta t), \cdots, x_\mu(\Delta t)\right]^T && (2)\\
\mathbf{F}(\Delta t) &\equiv \left[f_{-\mu}(\Delta t), \cdots, f_k(\Delta t), \cdots, f_\mu(\Delta t)\right]^T && (3)\\
f_k(\Delta t) &\equiv f_k(t) \sum_{\Delta t=-\infty}^{\infty} \delta\left(t - T_s \Delta t\right) && (4)\\
\Phi^{-1} &\equiv \Psi \Gamma_+ S \Gamma_- && (5)\\
\Psi &\equiv \frac{\tau}{T_s} && (6)\\
S &\equiv \mathrm{diag}\left[\mathrm{sinc}\left(-\mu\pi\Psi\right), \cdots, \mathrm{sinc}\left(n\pi\Psi\right), \cdots, \mathrm{sinc}\left(\mu\pi\Psi\right)\right] && (7)\\
\Gamma_+ &\equiv \begin{bmatrix} e^{j\frac{2\pi}{K}\{(-\mu)^2\}} & \dots & e^{j\frac{2\pi}{K}\{(-\mu)n\}} & \dots & e^{j\frac{2\pi}{K}\{(-\mu)\mu\}} \\ \vdots & \ddots & & & \vdots \\ e^{j\frac{2\pi}{K}\{i(-\mu)\}} & & e^{j\frac{2\pi}{K}\{in\}} & & e^{j\frac{2\pi}{K}\{i\mu\}} \\ \vdots & & & \ddots & \vdots \\ e^{j\frac{2\pi}{K}\{\mu(-\mu)\}} & \dots & e^{j\frac{2\pi}{K}\{\mu n\}} & \dots & e^{j\frac{2\pi}{K}\{\mu^2\}} \end{bmatrix} && (8)\\
\Gamma_- &\equiv \begin{bmatrix} e^{-j\frac{2\pi}{K}\{(-\mu)^2\}} & \dots & e^{-j\frac{2\pi}{K}\{(-\mu)k\}} & \dots & e^{-j\frac{2\pi}{K}\{(-\mu)\mu\}} \\ \vdots & \ddots & & & \vdots \\ e^{-j\frac{2\pi}{K}\{n(-\mu)\}} & & e^{-j\frac{2\pi}{K}\{nk\}} & & e^{-j\frac{2\pi}{K}\{n\mu\}} \\ \vdots & & & \ddots & \vdots \\ e^{-j\frac{2\pi}{K}\{\mu(-\mu)\}} & \dots & e^{-j\frac{2\pi}{K}\{\mu k\}} & \dots & e^{-j\frac{2\pi}{K}\{\mu^2\}} \end{bmatrix} && (9)
\end{aligned}
$$

where ^{T} denotes transpose, $\delta(t)$ denotes Dirac delta function, diag[$\cdot$] denotes diagonal matrix, n is the degree of harmonics of the switching frequency, and V denotes $K \times K$ permutation matrix explained bellow. The signals with Δt are the discrete-time signals with period T_s. With p and $\tilde{u}_p$ being the integer from $-\mu$ to μ, consider the vector $\mathbf{u} \equiv [-\mu, \cdots, p, \cdots, \mu]^T$ and also the vector $\tilde{\mathbf{u}} \equiv \left[\tilde{u}_{-\mu}, \cdots, \tilde{u}_p, \cdots, \tilde{u}_\mu\right]^T$ in which the element of $\mathbf{u}$ is permuted. Then, V satisfies the following equations

$$
\begin{aligned}
\tilde{\mathbf{u}} &= V\mathbf{u} && (10)\\
v_{l,m} &\equiv \begin{cases} 1, & \text{if} \quad l = \tilde{u}_p \text{ and } m = p \\ 0, & \text{otherwise} \end{cases} && (11)
\end{aligned}
$$

where $v_{l,m}$ is the element of V. When the array is the uniform linear array (ULA) with element spacing of half a wavelength, $\mathbf{F}(\Delta t)$ is given by

$$
\begin{aligned}
\mathbf{F}(\Delta t) &= \mathbf{a}(\theta) f(\Delta t) && (12)\\
\mathbf{a}(\theta) &\equiv \left[e^{-j\pi(-\mu)\sin(\theta)}, e^{-j\pi(-\mu+1)\sin(\theta)}, \cdots, e^{-j\pi(\mu)\sin(\theta)}\right]^T && (13)
\end{aligned}
$$

where $\mathbf{a}(\theta)$ is the steering vector of the array toward direction θ. And the received power P can be expressed as

$$P \equiv E[\mathbf{X}^H(\Delta t)\mathbf{X}(\Delta t)] \qquad (14)$$

where $E[\cdot]$ denotes expectation and ^{H} denotes Hermitian. From (1), (12), and (14), the received power P can be calculated.

3. Method of switching order optimization

In TDM-AAA, in the case that the switch-on time is extended to the limit in order to increase the received power, the received signals of the antenna elements are mixed [2], [3]. In this case, if the phases of the mixed signals are close to each other, then the received power of TDM-AAA is improved instead of being deteriorated. In the past study, we proposed the method of the switching order optimization that makes the phases of mixed signals close to each other [3]. In this section, the modified method of improving the received power by the switching order optimization is represented.

If the switching order is according to the antenna number, the correlation vector used in MMSE (Minimum Mean Square Error) algorithm [4] can be expressed by

$$\mathbf{r}_{xr} = E[\mathbf{F}(\Delta t)r^*(t)] = E[\Phi\mathbf{X}(\Delta t)r^*(t)] \tag{15}$$

where $r(t)$ denotes the reference signal, and * denotes complex conjugate. In (15), the noises are ignored because of no correlation with the reference signal. Assume that the single desired wave impinges on the array, and the correlation vector becomes

$$\mathbf{r}_{xr} = \xi\mathbf{a}(\theta) \tag{16}$$

where ξ is the complex constant. Since the phase differences of the array elements are found from the steering vector $\mathbf{a}(\theta)$, they are obtained from the correlation vector of (16).

The optimized switching order to reduce the phase differences of the mixed signals is obtained in the following steps: 1) Receive the desired signal with the switching in order of the antenna number, and calculate the correlation vector. 2) Define arbitrarily the first element of the switching order. 3) Compute the phase delay (or phase advance) of the other array elements. 4) As the next element of the switching order, select the element of the least phase delay (or phase advance) with the previous element. 5) Repeat 3) and 4) until the switching order is all determined. Once the optimized switching order is determined, the signals are received again with the optimized switching order and the adaptive algorithm is executed. With these steps, the calculation amount of the switching order optimization is less than the one with the steps in [3], while the improvement of the received power of the above-mentioned steps is still the same as the steps in [3].

4. Evaluation of received power improvement with switching order optimization

In [3], the received power improvement with the switching order optimization was confirmed in the case that the arrival direction of the desired signal was -70 degree. In this section, we evaluate the effectiveness of the switching order optimization in the case of all arrival directions of the desired signal via computer simulation. In the simulation, the ULA had 13 omnidirectional antenna elements and elements were spaced half a wavelength apart. The switching cycle T_s was 1μsec and no additional noise was assumed. As the switching order, the optimized order explained in **3.** is employed.

Table 1 shows the optimized switching order for each arrival direction from 0 to 90 degrees in 1 degree steps. "Peak angle" denotes the direction of the maximum received power with the each switching order except for 0 degree near. The direction of 0 degree means boresight of the array, at which the received signal phases of all antennas are the same. Therefore, the received power at 0 degree is always the maximum with any switching order. Because of the symmetry of the optimization results for arrival directions, the calculation is omitted from -90 to -1 degrees. As a calculating result, we have 24 optimized switching orders.

All received powers with each optimized switching order are shown in Fig.3. They are normalized by the received power at 0 degree. It is found that the received power can be optimized for all directions. In Fig.4, the received power with the ideal switching order about each arrival direction is presented in solid line. That is the maximum of the received power at each direction in Fig.3. Also the received power with the conventional switching order (according to the antenna number) is shown in dash-dot line. The figure indicates that, if the switching order is always optimized ideally, the received power keeps within only 0.3 dB down from the maximum. In addition, the received power with the ideal switching order

Table 1: Optimized switching orders for signal arrival directions

order no.	arrival directions	optimized order	peak angle	order no.	arrival directions	optimized order	peak angle
#1	0°	-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6	-	#13	31° ~ 33°	-6, 5, 1, -3, 4, 0, -4, 3, -1, -5, 6, 2, -2	32°
#2	1° ~ 9°	-6, 6, 5, 4, 3, 2, 1, 0, -1, -2, -3, -4, -5	9°	#14	34°	-6, 1, -3, 4, 0, -4, 3, -1, 6, -5, 2, -2, 5	33°
#3	10°	-6, 5, 4, 3, 2, 1, 0, -1, -2, -3, -4, -5, 6	10°	#15	35° , 36°	-6, 4, -3, 0, 3, -4, 6, -1, 2, -5, 5, -2, 1	36°
#4	11°	-6, 4, 3, 2, 1, 0, -1, -2, -3, -4, 6, -5, 5	11°	#16	37° ~ 41°	-6, -3, 0, 3, 6, -4, -1, 2, 5, -5, -2, 1, 4	38°
#5	12°	-6, 3, 2, 1, 0, -1, -2, -3, 6, -4, 5, -5, 4	12°	#17	42° ~ 46°	-6, 5, 2, -1, -4, 4, 1, -2, -5, 6, 3, 0, -3	46°
#6	13° , 14°	-6, 2, 1, 0, -1, -2, 6, -3, 5, -4, 4, -5, 3	14°	#18	47° , 48°	-6, 2, -1, -4, 4, 1, -2, 6, -5, 3, 0, -3, 5	47°
#7	15° , 16°	-6, 1, 0, -1, 6, -2, 5, -3, 4, -4, 3, -5, 2	15°	#19	49° ~ 53°	-6, -1, 4, -4, 1, 6, -2, 3, -5, 0, 5, -3, 2	50°
#8	17° ~ 19°	-6, 0, 6, -1, 5, -2, 4, -3, 3, -4, 2, -5, 1	18°	#20	54° ~ 56°	-6, 6, 1, -4, 3, -2, 5, 0, -5, 2, -3, 4, -1	56°
#9	20° , 21°	-6, 5, -1, 4, -2, 3, -3, 2, -4, 1, -5, 6, 0	21°	#21	57° , 58°	-6, 1, -4, 3, -2, 5, 0, -5, 2, -3, 4, -1, 6	57°
#10	22° , 23°	-6, -1, 4, -2, 3, -3, 2, -4, 1, 6, -5, 0, 5	22°	#22	59° ~ 62°	-6, 3, -4, 5, -2, 0, 2, -5, 4, -3, 6, -1, 1	61°
#11	24° ~ 26°	-6, 3, -2, 2, -3, 6, 1, -4, 5, 0, -5, 4, -1	25°	#23	63° ~ 65°	-6, 5, -4, -2, 0, 2, 4, -5, 6, -3, -1, 1, 3	64°
#12	27° ~ 30°	-6, -2, 2, 6, -3, 1, 5, -4, 0, 4, -5, -1, 3	27°	#24	66° ~ 90°	-6, -4, -2, 0, 2, 4, 6, -5, -3, -1, 1, 3, 5	67°

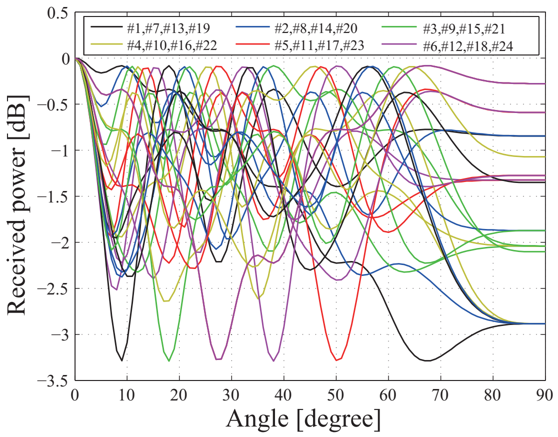

Figure 3: Received powers with switching order optimization for all directions.

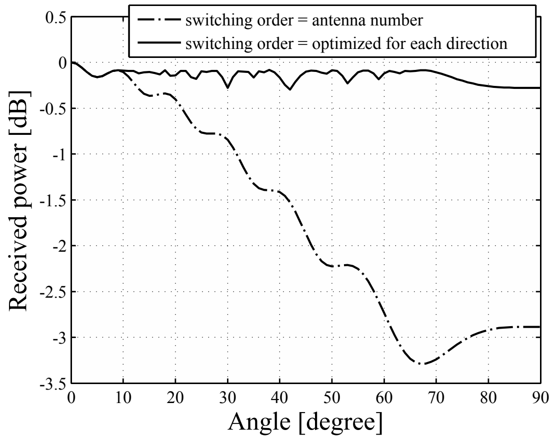

Figure 4: Received power comparison between optimized order and antenna number order.

is 3.2 dB higher than the one with the conventional order at the maximum, and 1.6 dB higher on the average. In this figure, it is represented that the switching order optimization is effective for the received power improvement.

5. Conclusion

In this paper, we have examined the switching order optimization in TDM-AAA when the receiving signal is incident on the ULA from all possible directions. After the received signals of the TDM-AAA were formulated, the process of the switching order optimization was shown. Via computer simulation, the switching orders were optimized for all directions and the corresponding received powers were calculated. As a result, it has been shown that the switching order optimization is effective for all directions. In future work, we will prototype the TDM-AAA and evaluate it in actual environments.

References

[1] E. Moriyama, Y. Kamio, K. Hamaguchi, H. Furukawa, “A CMA Adaptive Array Antenna System with a Single Receiver Using Time-Division Multiplexing,” IEICE Trans., Vol.E84-B, No.6, pp.1637-1646, June 2001.

[2] K. Koga, N. Kikuma, H. Hirayama, K. Sakakibara, T. Koike, H. Iwashita, Y. Mizuno, “A Study of Scale Reduction for an Adaptive Array with a Single Receiver Using Time-Division Multiplexing,” IEICE Technical Report, Vol.111, No.200, AP2011-65, pp.7-12, Sep. 2011.

[3] K. Koga, N. Kikuma, H. Hirayama, K. Sakakibara, T. Koike, H. Iwashita, Y. Mizuno, “A Study of Switching Methods for an Adaptive Array with a Single Receiver Using Time-Division Multiplexing,” IEICE Technical Report, Vol.111, No.429, AP2011-188, pp.31-36, Feb. 2012.

[4] N. Kikuma, *Adaptive Antenna Technology*, Ohmsha, Oct. 2003.