Adaptive Array Antenna for W-CDMA Systems

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The adaptive array antenna (AAA) is one of the advanced techniques that will be implemented in the IMT-2000 mobile telecommunications systems to achieve a high system capacity. This paper describes an integrated AAA system for W-CDMA that consists of both uplink and downlink beam formers. We developed three functions for the AAA: a digital beam former using the normalized least mean square (NLMS) algorithm, a two-dimensional path searcher that works at a lower reception level than the conventional one, and a calibrator that compensates for variations in the amplitude and phase of signals at antenna branches. We built an experimental test bed, conducted field trials, and evaluated characteristics of the AAA such as the compensation accuracy of the calibrator and the path search sensitivity of the path searcher. The experimental results showed that the AAA is effective enough to improve system capacity.

1. Introduction

The following problems[1)] will become critical when expanding the use of W-CDMA in the future:

1) Interference in low transmission rate signals caused by high transmission rate signals.

The number of users who use low transmission rates while high transmission rate communication is in progress will decrease because the high transmission rate signals will cause a large amount of interference in the low transmission rate signals.

2) There will be stronger demands to increase the number of users a base station (BS) can accommodate.

The number of users a BS can accommodate is limited by the mutual interference from the users' signals and other factors. Moreover, the area of a W-CDMA cell is smaller than that of a second-generation mobile communications system due to the restriction of transmission power. Therefore, to expand the use of W-CDMA, it will be necessary to increase the number of users that a BS can accommodate and also increase the cell area.

To solve these problems, we developed an adaptive array antenna (AAA) technology for a W-CDMA BS that reduces the amount of interference that is received. The new AAA makes it possible to increase the number of users. It also makes it possible to cover the same area with a smaller number of BSs than with conventional BSs.

In the previous fiscal year, we built an experimental system with AAA functions. We acquired a radio station license for the system at the beginning of this year, and we are now conducting field trials. We have already confirmed that the compensation accuracy of the calibrator, the path search sensitivity of the path searcher, and other characteristics have met our performance expectations.

Section 2 of this paper explains the essentials of AAA technology. Section 3 briefly describes the AAA technology that we developed, together with our experimental system. Lastly, Section 4 presents the results of a simulation we conducted and the results of our practical experiments.

2. The adaptive array antenna (AAA) as an interference reduction technology

2.1 Principle of the AAA

The salient feature of CDMA technology is its use of mutually orthogonal spreading codes to spread radio waves modulated with user signals over a wide bandwidth. This makes it possible to transmit, even concurrently, the users' original signals by using the same carrier frequency and with very little mutual interference.

The orthogonality between multiple users' signals, however, is distorted by multipath fading and by asynchronous signals from other users, leading to reduced transmission quality.

Strictly preventing the signals of users other than the desired user from being received can reduce the received interference signals, making it possible to increase the number of users a BS can accommodate.

The AAA technology uses multiple antenna elements and gives directivity to an antenna system that is made up of these antenna elements. The advantages of AAA are achieved by applying an appropriate weight to each of the signals received at the antenna elements and combining them so that unnecessary signals are suppressed. The technology utilizes the fact that the phases of the signals received at the antenna elements differ from one another according to the direction from which each signal is received and the arrangement of the array antennas.

Figure 1 illustrates the principle of AAA.

The following expression represents the sum of signals received at four antenna elements (A0 to A3) through a digital beam former (DBF):

$$E_{sum} = E_0 \sum_{k=0}^{3} A_k \exp\left\{ j\left(\frac{2\pi}{\lambda} d_k \sin\theta + \delta_k\right)\right\} \qquad (1),$$

where, A_k and δ_k are the adjustment items (weights) that are placed, respectively, on the amplitude and phase of a signal received at the k-th antenna element. These weights are adjusted so that the signals from the desired user are in phase at the output of the DBF, and therefore, the E_{sum} of those signals is maximized. To put AAA to practical use, it is also necessary to form beam nulls in the directions of the interference signals. One of the major functions of AAA technology is to calculate these weights by digital signal processing in real-time while tracking the movement of the mobile station (MS).

2.2 Uplink/downlink beam forming

For uplinks, summation of the signals from the antenna elements is done after setting weights for the signals so that the signal-to-interference plus noise ratio (SINR) is the largest for the combined signal from the desired user. This process is called beam forming. At the same time, the null points of the beam are steered towards interference signals. This is called null steering.

Theoretically, the least mean square (LMS) method is the most basic method for calculating the weights. However, in practice, improved methods, for example, the normalized least mean square (NLMS), are used so that the calculation becomes more stable and converges faster.

Beam forming increases the number of users that can be accommodated because it increases the sensitivity to the signals of the desired user

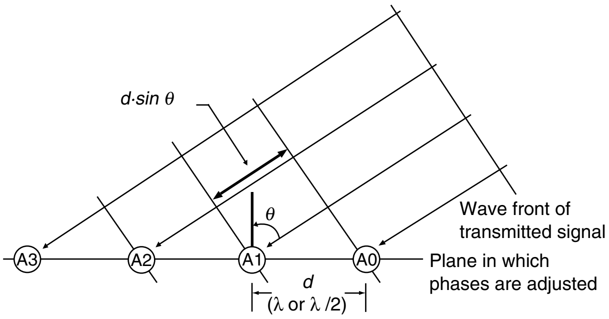

Figure 1
Principle of AAA.

while reducing the sensitivity to interference signals.

For downlinks, the ideal approach for digital beam forming is to control the beams for all users as a whole in such a way that the SINR at the MS of interest is the highest. This, however, is not practical, and the method currently in use is to control beams for individual users based on the direction of arrival (DoA) information acquired on the respective uplinks.

3. Proposed adaptive array antenna (AAA) configuration

3.1 AAA system

The AAA technology increases antenna gain by adjusting the phases of received signals to form beams. However, there are several technological problems to be solved before this technology can be put to practical use. The major problems include how to keep track of the directions of MSs, reduce the noise in a receiver to compensate for a possible reduction in the reception sensitivity of the antennas, generate downlink beams, and compensate for phase differences between receivers and between transmitters.

In the following sections, we describe the configuration of the BS we propose while keeping the above problems in mind. The overall configuration is shown in **Figure 2**.

- The NLMS method was adopted as the adaptive algorithm for AAA to converge the values of weights for beam forming and to further adjust the weights in response to environmental changes such as those caused by the movement of mobile terminals. NLMS enables high-speed convergence and tracking.
- Compared to a conventional system, the received signal power at each BS antenna in an AAA system is lower. This is because, at equal distances, the signal power from an MS in an AAA system is lower than that from an MS in a conventional BS system. However, a two-dimensional (2D) path searcher can recognize the path timing at a lower carrier

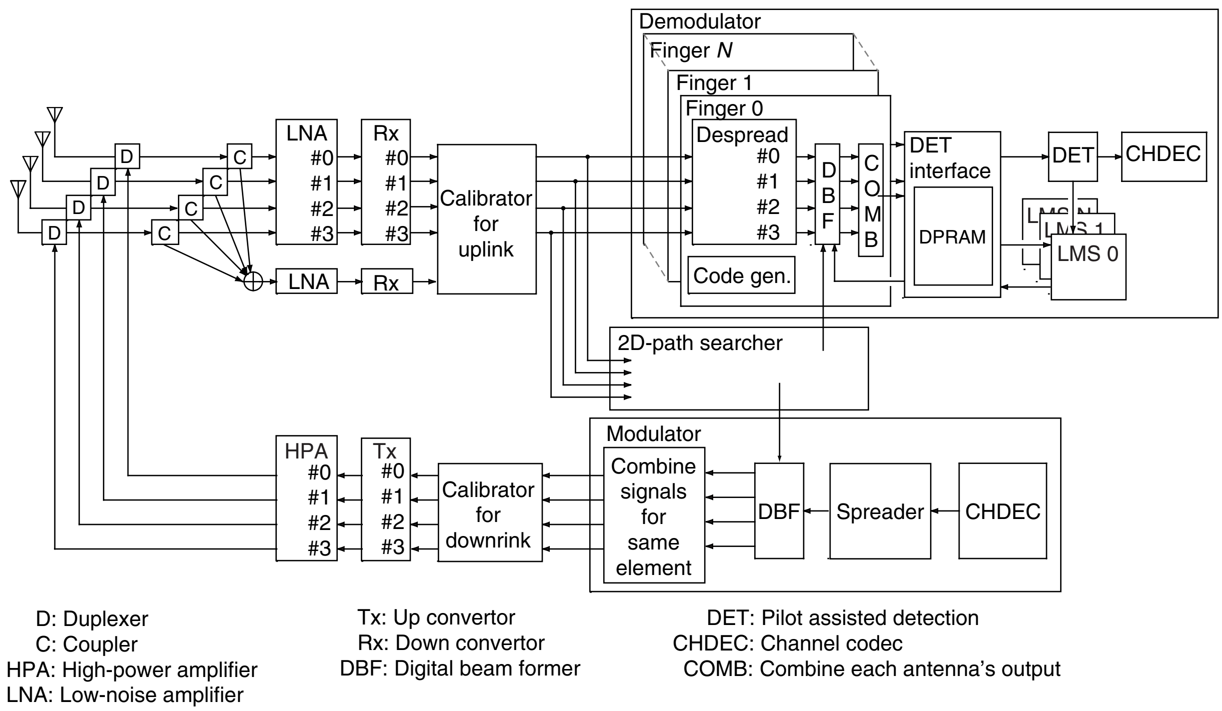

Figure 2
Overall configuration of proposed BS.

to noise ratio (C/N). "Two-dimensional" here means that the path searcher concurrently generates path timings and DoA estimates.

- The downlink beam is generated by DoA information detected by the 2D-path searcher.
- Any phase and amplitude variations between the individual components in the receiver must be compensated for, because the uplink DoA information is used in downlink beam forming. An uplink calibrator is used to compensate for these variations.

Table 1 shows the main specifications of the setup used in the experiments. The experiments used equally spaced linear array antennas. The antennas were set one wavelength apart from each other.

3.2 NLMS

The weights of the AAA for the uplink are updated using the NLMS algorithm. The digital processing of the algorithm should be carefully considered so that stable convergence is achieved in mobile communication environments. The step size, μ, of the conventional LMS algorithm is determined according to Equation (2), which contains the maximum eigenvalue (λ_{max}) of an autocorrelation matrix of the input signals so that the adaptive weights do not diverge.

Table 1
Main specifications.

Antenna configuration	Equally spaced four-element linear arrays
Antenna spacing	1 λ
Chip rate	3.84 Mcps
Sampling rate	15.36 Msps
Band limit	Root Nyquist roll-off (α = 0.22)
Measurement channel	AMR 12.2 kb/s
Beam forming method (uplink)	DoA, NLMS
Beam forming method (downlink)	DoA
Path search method	Two-dimensional path search
Uplink calibrator	Blind automatic calibrator

$$0 < \mu \leq \frac{2}{\lambda_{max}} \quad (2)$$

If μ is assumed to be a constant, however, the update size of a weight becomes small when the reception level is low, which delays the convergence of an adaptive weight.

The weight update equation of the NLMS algorithm we used is shown in Equation (3).

Assume that the initial value is $w(0) = [1, 0, 0, 0, \ldots, 0]^T$, where T denotes the transpose.

$$w_m(n+1) = w_m(n) + \mu' e^*(n)\, x_m(n) \quad (3)$$

$$\mu' = \frac{\mu}{\sum_{m=1}^{M} |x_m(n)|^2} \quad (4)$$

$$e(n) = ref(n) - y(n) \quad (5)$$

$$y(n) = \sum_{m=1}^{M} w_m^*(n)\, x_m(n) \quad (6),$$

where m(1 m M), $x_m(n)$, n, μ, $ref(n)$, $e(n)$, and * are, respectively, the antenna number, branch signal of the AAA, update number, step size, reference signal, error signal, and complex conjugate.

As can be seen from Equation (4), if the instantaneous total power of the branch signals is high, the NLMS algorithm reduces the step size μ' to minimize the changes in the update weights. Conversely, if the total power is low, the algorithm increases μ' to make the changes large. As a result, the step size μ' varies adaptively by following the changes in the input signal level. This prevents the update weights from diverging and makes the algorithm more stable and faster converging than when a fixed step size is used.

3.3 2D-path searcher

The path search characteristic of an array antenna can be improved with beam forming or by combining the correlator output power of each antenna. The estimation error of DoA deteriorates the path search characteristics. We therefore adopted the combining method to provide a more stable path search performance.

Figure 3 shows the block diagram of the 2D-path searcher we developed. A search is applied for the Dedicated Physical Channel (DPCH) as follows. The signals received at the antennas are processed through matched filters (MFs). Then, the signals are combined in phase using the pilot symbols in the slots to obtain the instantaneous correlation outputs. The path timing search section detects the path timing from the delay profile obtained by converting the amplitude to a power level and then combining the power of each antenna signal and averaging the resulting power with respect to time. The DoA search section provides a DoA profile by obtaining the phase differences between adjacent antennas and averaging the correlator output powers with respect to time. The DoA for a desired path is estimated by referencing the DoA profile with respect to the path timing detected from the delay profile.

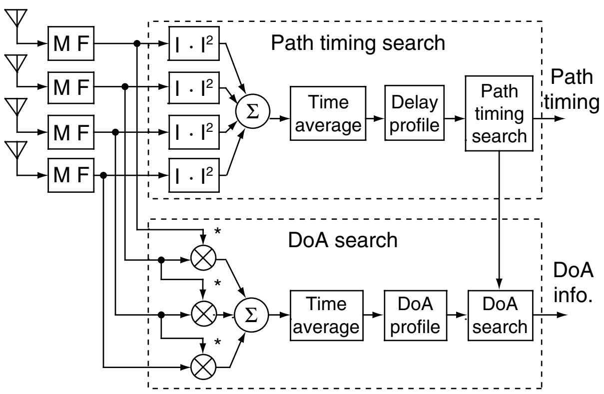

Figure 3
Block diagram of 2D-path searcher.

3.4 Calibrator

If an AAA realized by digital signal processing is used in an uplink, amplitude and phase deviations occur between antenna branches when the radio frequency (RF) signals are converted to digital signals. These deviations are due to mechanical and electrical variations in the RF components such as the amplifiers, mixers, and cables that occur over time because of temperature variations, aging, and other factors.

This section describes the configuration and features of the automatic calibration method,[2] in which the minimum mean square error (MMSE) method is used for the uplink calibrator.

Figure 4 shows the block diagram of an uplink AAA system that incorporates a circuit based on this calibration method. A reference signal for calibration is obtained by extracting portions of the received signals at the antenna branches using directional couplers and then combining them. This system is designed to minimize the difference between the reference signal and the

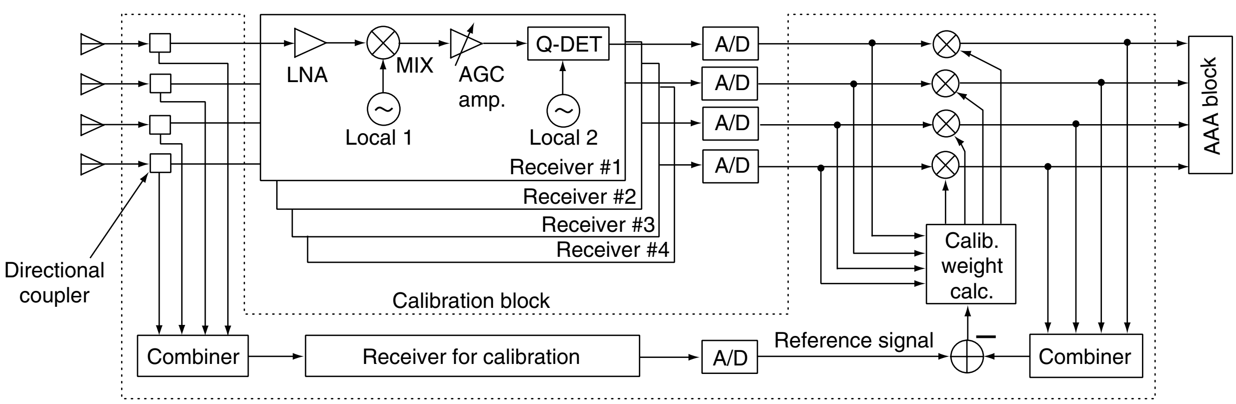

Figure 4
Four-element adaptive array antenna with calibration block for uplink.

combined weighted calibration signals.

This calibration method has the following features:

1) No additional reference signal is needed.
2) Calibration can be carried out without interfering with communications.
3) No demodulation is needed, because the user-multiplexed signals are used to calculate the calibration weights.

Equation (7) shows the update expression for the calibration weights.

$$h_m(N+1) = h_m(N) + \mu_0 \cdot \frac{1}{B} \cdot \sum_{t=1}^{B} \left\{ e^*(t) \cdot x_m(t) \Big/ \sum_{k=1}^{M} |x_k(t)|^2 \right\} \quad (7),$$

where $h_m(N)$, μ_0, B, $e(t)$, $x_m(t)$, and M represent, respectively, the calibration weight for the m-th branch at the N-th iteration, the step size, the block period, the error signal at time t, the signal on branch m at time t, and the number of branches involved.

Because the signal to noise ratio (SNR) of the signals at antenna branches is usually a minus value in a W-CDMA system, this calibrator should work properly when the signals are buried in noise. To cope with signals in this situation, the correlation values between the error signal $e(t)$ and each signal $x_m(t)$ are integrated over a certain period B and then averaged. This averaged value is added to the previous calibration weight to update it. In addition, to cope with the large changes in signal levels in mobile communication environments, the NLMS algorithm is used as the MMSE method.

Table 2
Link parameters (uplink).

Chip rate	3.84 Mcps
Modulation	Data: BPSK, Spreading: HPSK
Slot structure	DPDCH: 40 symbols DPCCH: 10 symbols (Pilot: 6 symbols)
Information bit rate	12.2 kb/s
Symbol rate	DPDCH: 60 ksps DPCCH: 15 ksps
Spreading factor	DPDCH: 64 DPCCH: 256
Channelization code	Walsh-Hadamald sequence
Scrambling code	Truncated-Gold sequence
Channel model	3GPP Case 1, speed 3 km/h
I/Q power ratio	DPCCH/ DPDCH: −5.46 dB
Number of users	1, DoA: 0°
Channel coding & decoding	Convolutional coding (R = 1/3, k = 9) Soft-decision Viterbi decoding
Interleaving length	10 ms

note) HPSK: Hybrid phase shift keying
DPDCH: Dedicated physical data channel
DPCCH: Dedicated physical control channel

4. Results of simulation and experiments

4.1 NLMS

We acquired the convergence characteristics of the NLMS in experiments. For the experiments, we used an antenna array consisting of four antenna elements, a linear array configuration, and an antenna spacing of 1 λ. The link parameters used in the experiments are shown in **Table 2**.

Figure 5 shows the weight convergence characteristic of NLMS when the average bit error rate (BER) is 10^{-2} and 10^{-3}. The lines in this figure represent the real part of each weight when the initial weight value for antenna branch 1 is 1 and that for the other antenna branches is 0. As can be seen from the figure, it takes about 110 slots (73 ms) for the weights to converge when the average BER is 10^{-2} and about 30 slots (20 ms) when the average BER is 10^{-3}. In a service that requires

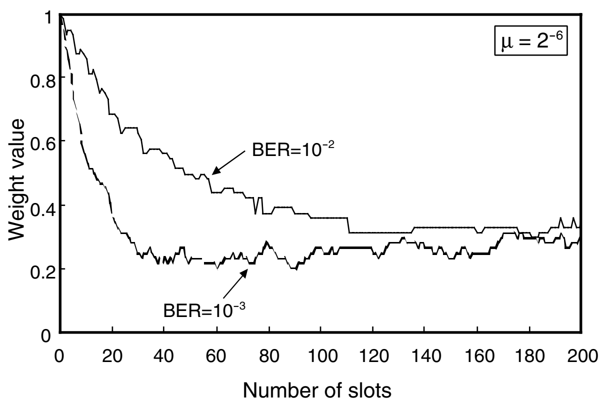

Figure 5
Weight convergence characteristics of NLMS.

an average BER of 10^{-3}, for example, the previous communication state can be resumed within about 20 ms, even if one of the valid paths of a communicating user is switched.

4.2 2D-path searcher

Figure 6 shows the cumulative probability function of path detection (CPF) when this searcher is applied to the DPCH in W-CDMA. The number of pilot symbols in a slot is 6. When the 2D-path searcher recognizes that a peak has been found in ±0.5 chips (five samples) of a delay profile and that a threshold value has been exceeded, the path timing detection is judged to be successful. The threshold value is 99% of the thermal noise distribution, as obtained from the distribution of the MF input signals and the number of times that averaging is performed. For a four-antenna combination, the timing detection probability versus Ec/No at PDP = 0.5 was improved by about 4 dB relative to single-antenna operation. This is an effect of combining the power of the signals from the antenna elements.

4.3 Calibrator

This section describes the results of the experiments we conducted to investigate the calibration method proposed in Section 3.

Because these experiments were intended to demonstrate the operation of the calibration method in a real W-CDMA environment, the SNR of the user-multiplexed signal to be handled was set to −4, −6, −8, and −10 dB, as measured at the antenna branches.

Table 3 shows the technical data used in the experiments.

Figure 7 shows the post-calibration phase error versus the phase deviation setting (with no amplitude deviation) when the S/N value was set to −4, −6, −8, and −10 dB (S is the summation of user-multiplexed signals received at the antenna branches, and N is the thermal noise with a receiver noise figure of 2 dB). The figure shows that the respective phase deviations are corrected to within 1.0°, 1.6°, 3.7°, and 5.1°, respectively. When the post-calibration phase error is 4°, for exam-

Table 3
Technical data used in the experiments.

Array antenna configuration	Two branches
Coupling degree of the directional coupler	−10 dB
Step size (μ_0)	1.0
Averaging period (B)	2^{16} samples
Test signals	Gaussian distribution, branch-independent
Initial amplitude deviation	−6.0 dB (for branches 1 and 2)
Initial phase deviation	−180 to 180° in steps of 30° (for branches 1 and 2)

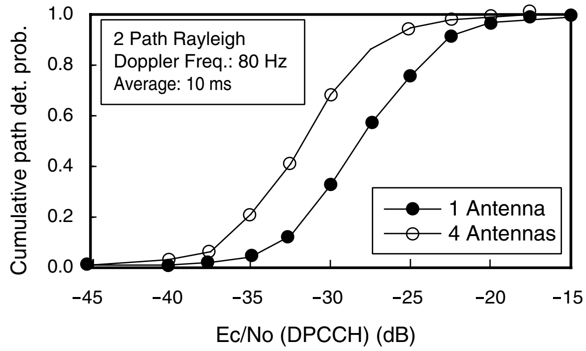

Figure 6
Cumulative probability function of path detection.

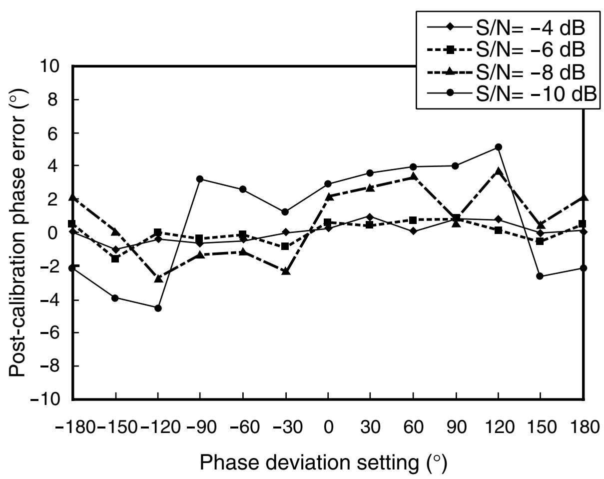

Figure 7
Post-calibration phase error.

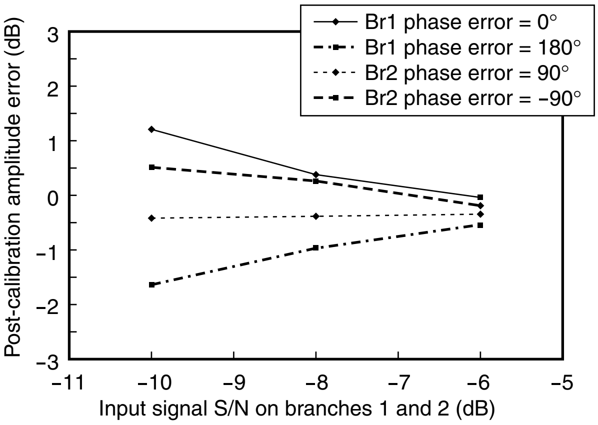

Figure 8
Post-calibration amplitude error.

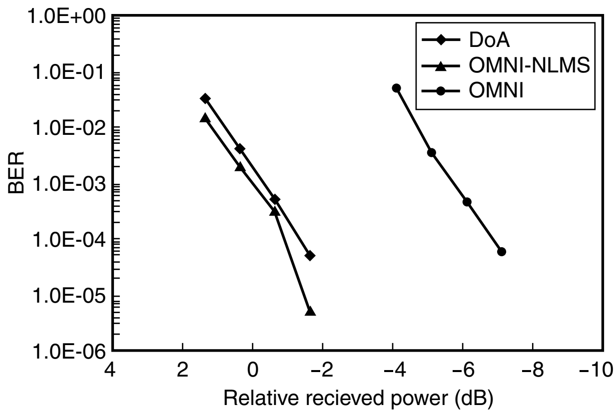

Figure 9
BER performance.

ple, the DoA estimation error for a user signal is 0.7°, which is satisfactory even at an input level of S/N = –8 dB (when the antenna spacing and the true DoA value for the user signal are 1 λ and 30°, respectively).

Figure 8 shows the post-calibration amplitude error when the amplitude deviation is set to –6 dB versus the user multiplexed signal S/N measured at antenna branches 1 and 2. Four curves are given: when the phase deviations at branch 1 are 0° and 180° and when the phase deviations at branch 2 are 90° and –90°. As can be seen, the amplitude error in the worst case is reduced to 0.5, 1.0, and 1.6 dB when S/N = –6, –8, and –10 dB, respectively.

4.4 Field test

The setup described above was used to confirm the reception characteristics obtained through beam forming.

The frequency used in the experiments was 3.32/3.38 GHz (uplink/downlink), and the antenna was a dipole. The BER performance in static channels was measured at a fixed point without transmission power control (TPC).

The MS used in the experiments conformed to the 3GPP specification.

Figure 9 shows the BER performance. For the horizontal axis, the relative received power was assumed to be 0 dB for a BER of 10^{-3} when the NLMS algorithm was used. Two beam-forming methods were evaluated: one of them uses weights obtained by DoA and the other uses weights that are converged with the NLMS method, starting from omnidirectivity. It was confirmed that both of these beam-forming methods improve the antenna gain by 5.5 dB or more.

Convergence comparisons and the tracking characteristics in mobile environments will be reported separately.

5. Conclusion

Our experiments produced the following results:

1) NLMS provided weights in digital beam forming that had a sufficiently high convergence characteristic within two frames when the BER was 10^{-3}.
2) The searcher achieved the same path detection performance as conventional methods at a C/N that was –4 dB lower than the C/N in conventional methods.
3) The calibrator compensated for amplitude and phase deviations among antenna elements, keeping the DoA estimation error at or below 0.7° when the SNR was –8 dB.
4) The antenna gain of the AAA was 5.5 dB (static characteristic) in the field trials.

These results show that AAA has the expected gain characteristics. We are currently experimenting with the interference reduction characteristics and will report our findings separately.

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