New Technology Report

Beam and Null Simultaneous Steering Space-Time Equalizer for Broadband Mobile Radio Communications

In mobile multimedia communications, Co-Channel Interference (CCI) and Inter-Symbol Interference (ISI) are major problems to overcome. Joint space and time equalizers (S/T-Equalizer) are considered most effective in solving these problems.

This article describes a beam and null simultaneous steering Space-Time Equalizer (S/T-Equalizer). The S/T-Equalizer performs separated S/T-signal processing in order to reduce computational complexity to a practical level. The S/T-Equalizer was prototyped. A series of field tests were then conducted using the 5 GHz frequency band to evaluate the transmission performance of the S/T-Equalizer. The results show that the S/T-Equalizer can reduce the ISI effects while maintaining reasonable signal strength, thereby improving BER (Bit Error Rate) performance.

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1. Introduction

Mobile multimedia communications demand the creation of broadband signal transmission techniques that offer transmission rates of tens of Mbps [1]. These techniques must overcome problems such as Co-Channel Interference (CCI) and Inter-Symbol Interference (ISI), as well as the relatively large propagation loss inherent to broadband mobile communications. Joint Space-Time Equalizer (S/T-Equalizer) is considered most effective in reaching these goals [2].

Figure 1 shows the structure and operating principle of the S/T-Equalizer. It consists of a temporal equalizer placed after an Adaptive Array Antenna (AAA) as shown in the figure. The AAA eliminates CCI as well as long delay signals that exceed the temporal equalizer range, while the temporal equalizer combines any applicable delay signals within its range. The temporal equalizer not only reduces the number of interference signals for AAA, but it can also obtain path diversity effects.

Allocating responsibilities to the AAA and the temporal equalizer separately this way in the space-time equalizer significantly improves transmission performance compared to operation with either of these techniques individually.

S/T-Equalizers are classified as two-dimensional (joint spatial and temporal) optimization types [2] and separated signal processing types [3][4] depending on how they process signals. Two-dimensional optimization types achieve optimum transmission performance because they process signals in space and time simultaneously, but because they have a large number of estimating parameters, they are too complex to implement. Separated signal processing types on the other hand process signals separately. This separation reduces the computational complexity of signal processing to a practical level.

Among separated signal processing-type S/T-Equalizers,

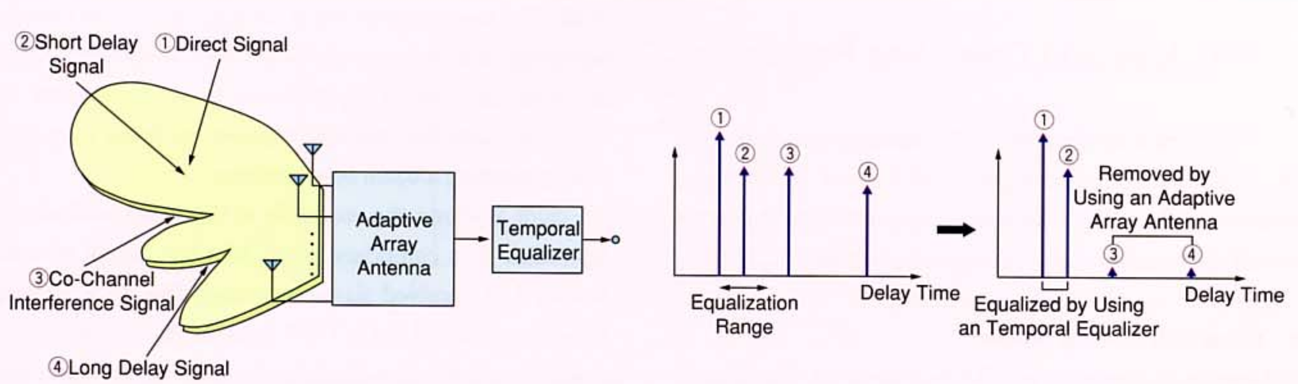


Figure 1 S/T-Equalizer Structure and Operating Principle

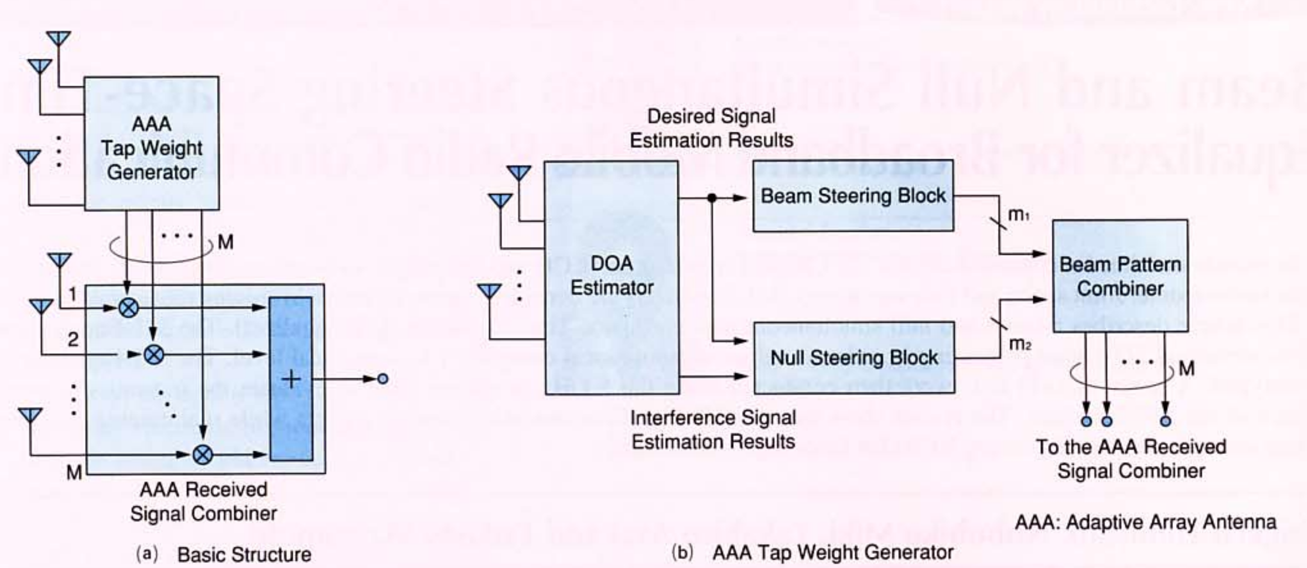


Figure 2 Beam/null Simultaneous Steering AAA

there is a beam/null steering-type [7] comprised of a beam/null steering-type AAA [5], and a Delayed Decision Feedback Sequence Estimation (DDFSE)-type adaptive equalizer [6]. The beam/null steering method steers a sharp beam towards a desired signal direction by beam steering and steers a deep null in the interference signal direction by null steering. This minimizes any loss of reception power and effectively eliminates interference signals. The DDFSE also reduces the number of states in the viterbi algorithm used for Maximum Likelihood Sequence Estimation (MLSE) and is a good choice because it can equalize relatively long delay signals using a reasonable number of calculations.

At DoCoMo, a prototype of the beam/null steering-type S/T-Equalizer was built in order to conduct field tests. The following section describes the structure and operating principle of the beam/null steering-type S/T-Equalizer, followed by a brief outline of the prototype and a report on field test results.

2. Structure and Operating Principle

The beam/null steering-type S/T-Equalizer prototype consists of a beam/null steering-type AAA and a DDFSE-type adaptive equalizer. The following section describes the structure and operation of each of these components.

2.1 Beam/Null Steering Method

A beam/null steering-type AAA estimates the Direction of Arrival (DOA) of each received signal, and then generates an AAA beam pattern based on the estimation. All antenna elements are hypothetically separated into beam steering elements and null steering elements to generate AAA beam patterns. The tap weight for each antenna element is calculated separately and the tap weights are then combined to generate beam patterns for signal transmission. Generating separate beam patterns this way requires far fewer calculations than generating a batch beam pattern.

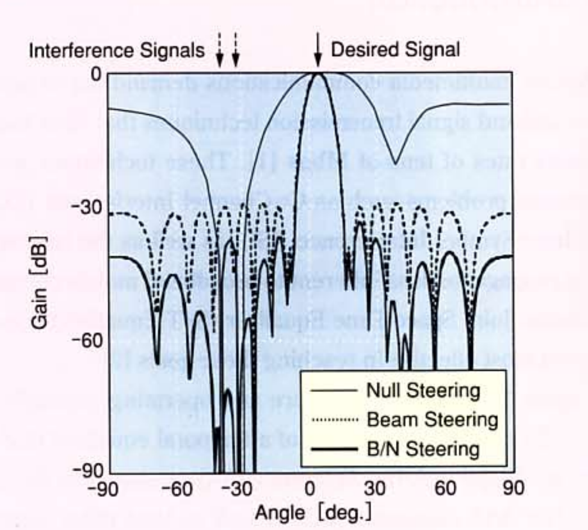


Figure 3 Example of Generated Beam Patterns

Figure 2 shows the structure of the beam/null steering-type AAA. It is comprised of an AAA tap weight generator and an AAA received signal combiner. The AAA tap weight generator consists of a DOA estimator, a beam steering block, a null steering block and a beam pattern combiner. Figure 3 shows an example of the beam pattern generated by the beam/null steering-type AAA. It is assumed here that the desired signal (solid line) and the two interference signals (dashed lines) are received in the direction indicated by the arrow.

In the AAA tap weight generator shown in Figure 2, the DOA estimator first uses the DOA estimation algorithm to estimate the direction from which a signal is received. A multiple signal classification (MUSIC) algorithm [8] was used in the prototype. Next, AAA beam patterns are generated by the beam steering block, null steering block and beam pattern combiner based on the estimation results.

For explanatory purposes here, let M be the total number of antenna elements, m_1 the number of beam steering elements and m_2 the number of null steering elements. A beam pattern (beam direction: 0°) is generated beforehand for m_1 elements with a sharp beam in the beam steering block and is used to calculate the beam pattern that will steer the beam towards the desired signal direction. An example of this beam pattern is indicated in Figure 3 by the dashed line.

A beam pattern derived from the Taylor distribution (side lobe level: −30 dB) like that shown in Figure 3 was used in the prototype, and here it is given that the sharp beam was steered towards the desired signal direction. Since a null has not been formed in the interference signal direction, however, only a fixed amount of attenuation could be determined for interference signals.

In the null steering block on the other hand, the DOA estimation results for desired and interference signals were used to steer the beam towards the desired signal direction and to generate the beam pattern for the m_2 elements that will steer the null towards the interference signal direction. An example of the pattern generated is indicated by the fine solid line in Figure 3.

The Howell-Applebaum algorithm [9] was used to generate the beam pattern in the prototype. It is clear from the figure that the deep null was steered towards the interference signal direction. Even though the beam was steered towards the desired signal direction, it was impossible to steer a sharp beam like that generated in the beam steering block.

Finally tap weights for the m_1 and m_2 elements were combined through convolution in the beam pattern combiner to generate an M element AAA beam pattern.

This pattern is indicated by the thick, solid line in Figure 3. It is clear from this figure that the sharp beam is steered towards the desired signal direction and the deep null is steered towards the interference signal direction.

The tap weight for all AAA elements calculated by the AAA tap weight generator in the AAA received signal combiner is complex multiplied by each received signal and the results are added together to output an AAA combined signal.

2.2 DDFSE

DDFSE is used to reduce the number of states in the viterbi algorithm used to perform the MLSE. Taps in the replica generator that have a number of states because of all the transmitted signal candidates are read from path memory along with the path histories for these tap states. The symbol candidates determined by these tap histories are split into fixed taps to reduce the number of viterbi states and thereby

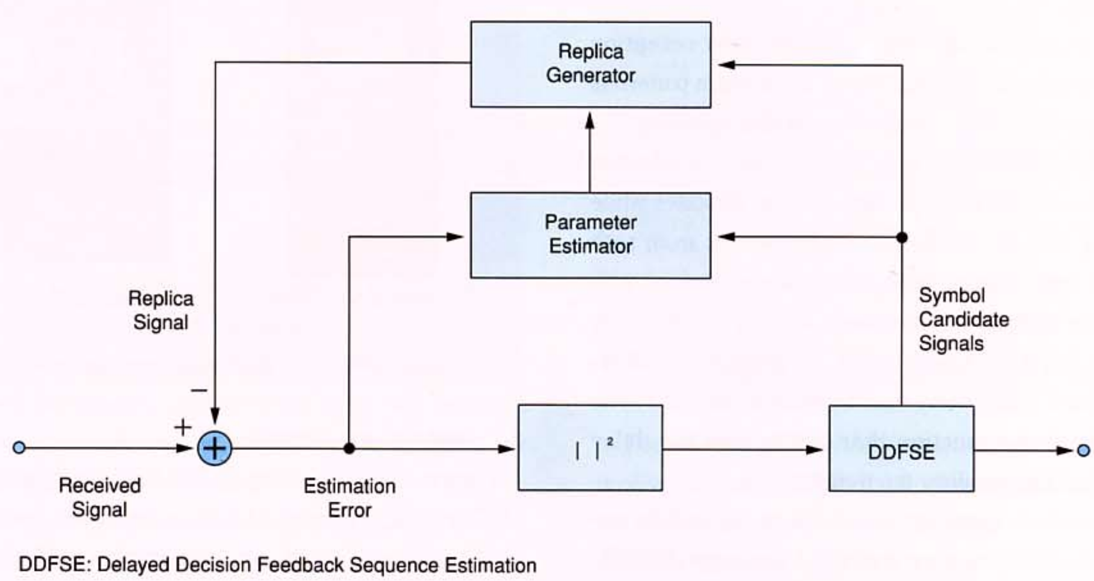


Figure 4 DDFSE-type Adaptive Equalizer

cut all calculations up to real values.

Figure 4 shows the structure of a DDFSE-type equalizer. Structured like an MLSE-type equalizer [10], it generates replica signals from the symbol candidates output from the DDFSE block. It processes the viterbi algorithm based on the results of a comparison between the received signals (AAA output signals) and the replica signals.

3. Field Test Results

A prototype of a beam/null steering-type S/T-Equalizer was built. The following briefly describes the prototype along with the results of field tests.

3.1 Prototype Details

Table 1 provides details regarding the prototype, and Photo 1 shows the prototype itself. It uses the Time Division Multiple Access (TDMA)/Frequency Division Duplex (FDD) system for access and the Gaussian-filtered Minimum Shift Keying (GMSK) system for modulation. The frequency band is 5 GHz and the transmission rate is 1.5 Mbits/s × 4 channels.

The beam/null steering-type S/T-Equalizer is used as a receiver at the Base Station (BS). BS signal transmission antenna element M is 19, beam steering element m_1 is 16, and null steering element m_2 is 4.

The prototype uses a beam pattern derived from the Taylor distribution for beam steering and the Howell-Applebaum algorithm for null steering. It uses eight array antennas and a MUSIC algorithm to estimate the DOAs of received signals.

With this prototype, the path with the most reception power is selected for the desired signal and a beam pattern is generated that will steer the beam towards that direction.

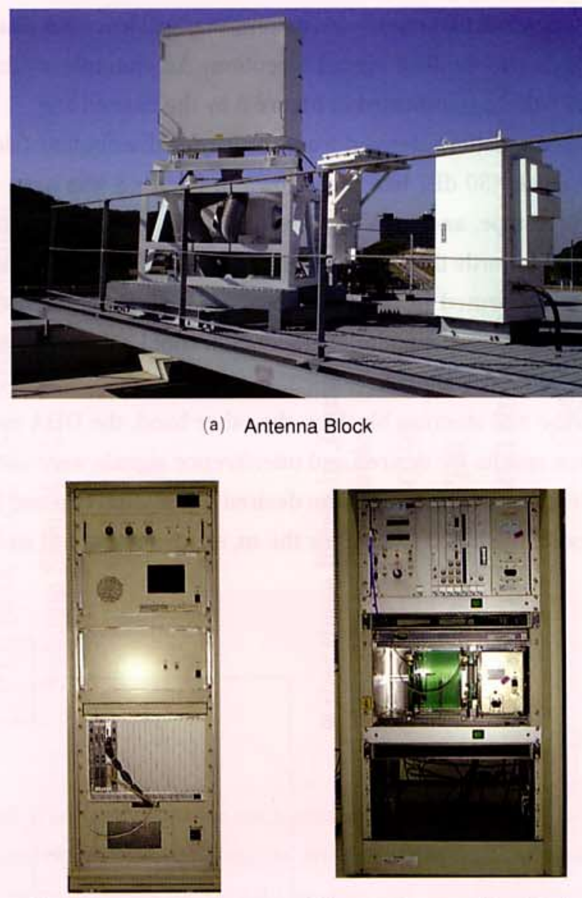
The number of taps used with the DDFSE-type adaptive equalizer was set to be 15. Four taps covered all states while the remaining 11 taps merely provided feedback from path memory. The same transmission performance obtained with the MLSE type can be obtained here as long as the delay time is within $3T$ ($1/T$: symbol rate). All delay wave effects can be eliminated with a delay time between $4T$ and $14T$. The prototype also has a function that determines the delay spread based on the equalizer tap weights.

An omni-directional antenna was used as the mobile station antenna and the receiver contained the same DDFSE-type adaptive equalizer as the BS.

Table 1 Specifications of Prototyped System

Access Scheme	TDMA/FDD
Modulation Method	GMSK
Frequency Band	5 GHz
Transmission Bit-Rate	1.5 Mbit/s x 4 Channels
Number of Antennas Elements for Signal Reception	19
Number of Antennas Elements for DOA Estimation	8
Mobile Station Antenna	Omni-Directional Antenna
Temporal Equalizer	8-state, 15-tap DDFSE

DDFSE: Delayed Decision Feedback Sequence Estimation
FDD: Frequency Division Duplex
GMSK: Gaussian-Filtered Minimum Shift Keying
TDMA: Time Division Multiple Access



(a) Antenna Block

(b) Beam Control Block (c) Adaptive Equalizer Block

Photo 1 Prototype Pphotographs

3.2 Field Test Conditions

Figure 5 shows a map of the test site located near the DoCoMo R&D Center. The BS antenna was installed on the roof of the center at a height of about 20 m above the ground. The direction from which the signal arrived was defined as shown in Figure 5.

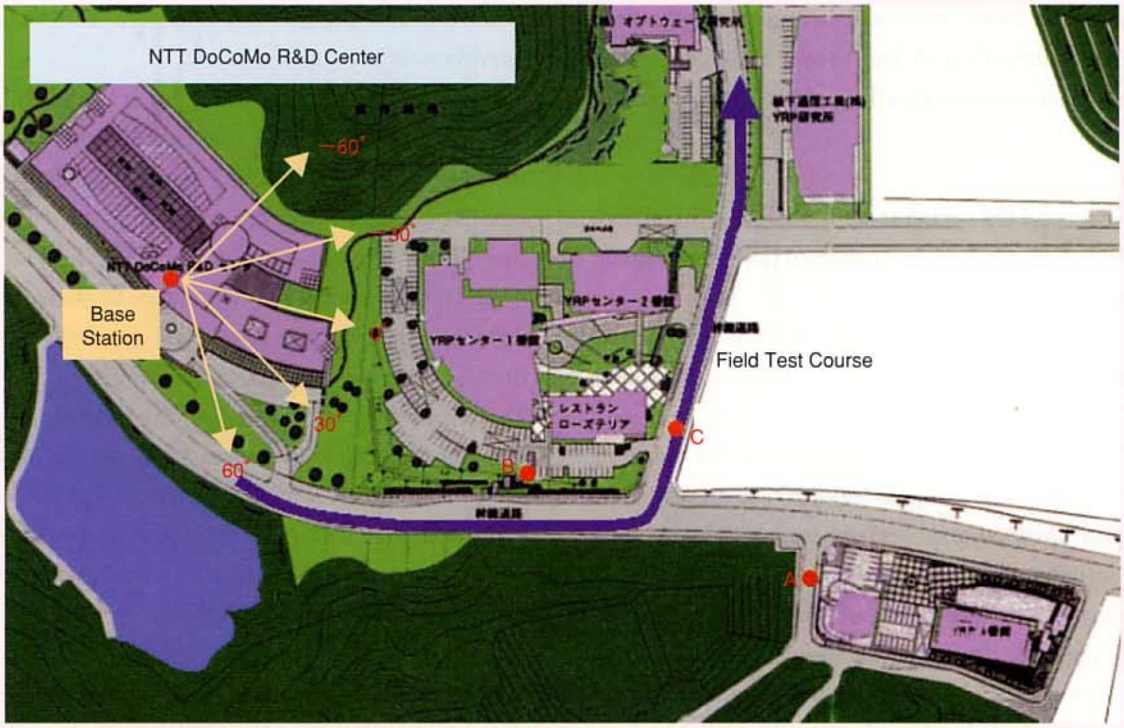


Figure 5 Measurement Course for Field Tests

The first test was conducted with the mobile station stationary in order to evaluate basic performance, and then the next test was conducted with the mobile station in motion. Bit Error Rate (BER)s for the uplink were measured in order to evaluate the transmission performance for the beam/null steering-type S/T-Equalizer.

An interference station was not set up in this test, and the nulls of the generated beam pattern were steered towards the delay path directions of the desired signal.

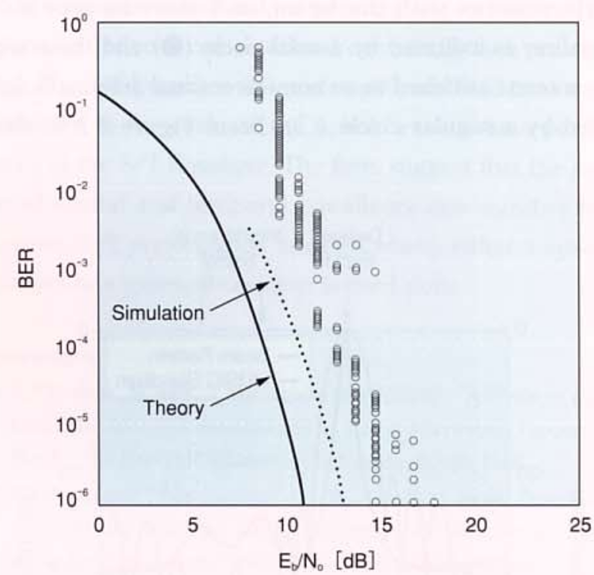
3.3 Stationary Test

The BER performance with the mobile station stopped at points A, B and C in Figure 5 was evaluated, and the following results were obtained.

(1) Point A

Point A has Line-of-Sight (LOS) paths from the BS and, based on arrival direction estimation results, it was confirmed that one wave was picked up here. The delay spread derived from the adaptive equalizer tap factor was less than 1*T*. This seems to indicate that the BER performance is the same as the static BER performance.

Therefore the BER performance was evaluated at Point A to check the basic operation and performance of the prototype. Figure 6 shows the BER performance at this position according to the field test.



BER: Bit Error Rate

Figure 6 BER Performance at Point A

The value of all the AAA elements combined was used for received signal E_b/N_0 on the horizontal axis. An average BER over a 0.5-second period was obtained, and the result is indicated by the circle (○) in Figure 6. The GMSK theoretical curve under the static condition is indicated by the solid line, and the computer simulation result is indicated by the dashed line for comparison. Compared to the computer simulation at the point BER = 10^{-5}, actual results from the field test indicated degradation of less than 2 dB as shown in Figure 6 and thus confirmed that the equalizer was operating effectively.

(2) Point B

Point B is a non-LOS region from the BS and the arrival direction estimation results clearly showed that three signals were picked up at this position.

In order to confirm the impact of the AAA, the BS-receiving antenna was also evaluated as an omni-directional antenna, and the results were compared.

The MUSIC spectrum obtained from the DOA estimation is indicated by the dashed line in Figure 7. It is clear from the figure that three signals arrived from −13°, 11° and 30°. The reception power estimate based on the DOA estimation was greatest for the signal arriving from −13°. This, therefore, became the desired signal direction and the beam was steered towards −13°. The other two signals were considered as interference signals and a beam pattern was generated to steer the nulls towards those directions. The beam pattern in this case is indicated by the solid line in Figure 7.

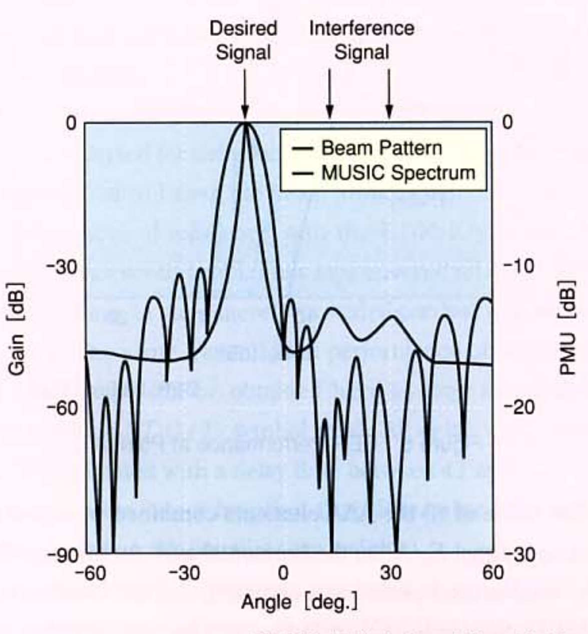
Figure 8 shows the BER performances at this position.The performances with the beam/null steering-type S/T-Equalizer is indicated by a solid circle (●) and those with the antenna switched to an omni-directional antenna is indicated by a regular circle (○). From Figure 8 it is clear that the BER performance is significantly better with the beam/null steering-type S/T-Equalizer. The reasons for this improvement are outlined below.

Since all three signals appearing in the MUSIC spectrum in Figure 7 were received with the omni-directional antenna, the delay spread was a fairly large 3.5T. The DDFSE-type adaptive equalizer achieved the same performance as that of the MLSE-type equalizer up to a delay time of 3T, which means that transmission performance degrades with a larger delay like this. By way of contrast, the delay spread is less than 1T with the beam/null steering-type S/T-Equalizer. This is because signals received with a significant delay were eliminated because the beam width was narrowed by the AAA. Superior performance was obtained as a result.

From the preceding statements, it is clear that the delay spread can be reduced and that transmission performance can be improved using an AAA.

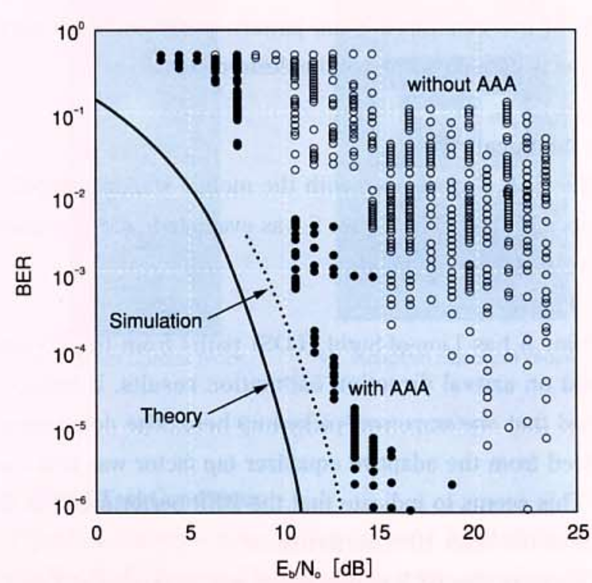
(3) Point C

Point C is also a non-LOS region from the BS. Figure 9 shows the BER performance at this position. The performance with a beam/null steering-type S/T-Equalizer is indicated by a solid circle (●) and that without an adaptive equalizer (using an AAA only) is indicated by a regular circle (○). The AAA output delay spread derived from the adaptive equalizer tap factor was 2.5T. It is clear from the DOA estimation and delay profile measurement results that multiple delay paths arrived from virtually the same direction at this



MUSIC: Multiple Signal Classification

Figure 7 MUSIC Spectrum and Beam Pattern at Point B



AAA: Adaptive Array Antenna
BER: Bit Error Rate

Figure 8 BER Performance at Point B

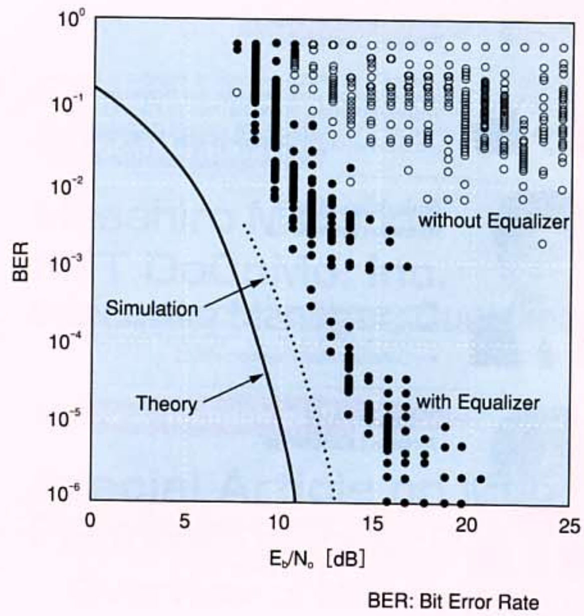


Figure 9 BER Performance at Point C

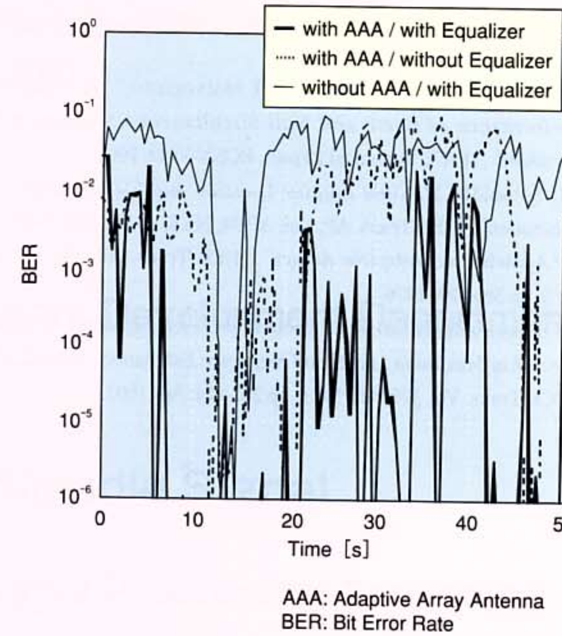


Figure 10 BER Performance for Average Vehicle

position. Therefore, merely narrowing the beam width using an AAA significantly degraded transmission performance due to the delay path effect that occurred using an AAA alone. This happened with virtually no decrease in the delay spread. With an S/T-Equalizer that had both an adaptive equalizer and an AAA on the other hand, the delay path could also be used for signal power.

This can significantly improve transmission performance, yielding virtually the same performance as that at Point A. From the preceding results, it was confirmed that use of an adaptive equalizer in conjunction with an AAA proved extremely effective if delay paths with a significant delay spread arrived from the same direction.

3.4 In-motion Experiment

Figure 10 shows the BER performance at an average vehicle speed of 30 km/h over the course shown in Figure 5. The performance with a beam/null steering-type S/T-Equalizer is indicated by the thick, solid line, that using an AAA alone is indicated by the fine line, and that using an adaptive equalizer alone is indicated by the dashed line. Points with a BER worse than 10^{-2} appeared relatively often when either an AAA or an adaptive equalizer was used alone, but a BER below 10^{-4} occurred at almost every point when both devices were used together. These results confirmed that BER performance could be significantly improved using a S/T-Equalizer as opposed to using either an AAA or an adaptive equalizer alone.

4. Conclusion

In this article, we have described a new S/T-Equalizer featuring separated spatial and temporal signal processing. This separation reduces computational complexity to a practical level. The S/T-Equalizer was prototyped, and field tests were conducted to the evaluate the uplink transmission performance of the S/T-Equalizer. The tests suggest that the joint use of spatial and temporal equalizers can significantly improve BER performance in cases where either a spatial equalizer or a temporal equalizer is used alone.

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