Field Trial of Space–Time Equalizer and Delay Diversity Transmission in Uplink for TDMA Mobile Communication

Takeshi Toda, Member, IEEE, Yuukichi Aihara, and Jun-ichi Takada, Member, IEEE

Abstract—Space–time (ST) equalizer and delay diversity transmission (DDT) were field tested in uplink for a time-division multiple-access mobile communication system. The ST equalizer used a cascade connection of constrained array processors and branch-metric-combining (BMC) maximum-likelihood sequence estimation which was designed to provide both space- and path-diversity gains from first-arrival and one-symbol-delay paths while suppressing excessive intersymbol interference. DDT with two antennas was used for the mobile transmitter to ensure sufficient path diversity at the ST equalizer in a small-delay-spread environment. Test results showed that the ST equalizer bit error rate (BER) was significantly better than an ST equalizer without BMC and a single array processor for both micro- and macrocell environments. Furthermore, the ST equalizer BER with DDT was better than that without DDT for the microcell environment.

Index Terms—Adaptive array, delayed diversity transmission, intersymbol interference (ISI), maximum-likelihood sequence estimation (MLSE), space–time equalizer.

I. INTRODUCTION

HIGH-DATA-RATE mobile communication systems based on time-division multiple-access (TDMA) require space–time (ST) equalization to improve the receiver’s performance by combating excessive intersymbol interference (ISI). In particular, an ST equalizer using an antenna array and a maximum-likelihood sequence estimation (MLSE) can provide both space- and path-diversity gains. In the ST equalizer, the antenna array presystem combines spatial-domain multiple received paths to provide a space-diversity gain. This is done while suppressing excessive ISI beyond the sequence estimation range of the MLSE subsystem without increasing hardware complexity, even if the delay time increases. The MLSE then obtains a path-diversity gain by using short-delay ISI signals extracted by the antenna array [1]–[7].

Various types of ST equalizers have been investigated through computer simulation [1]–[7]. The performance in a simulation greatly depends on having realistic ST propagation scenarios though, and thus it must still be eventually evaluated in the field. However, only a few reports of field trials have been made [8], [9] probably due to the cost and time. As an alternative evaluation method, link/system-level simulations using field measurement data have been tried [10]. Still, to enable practical use of an ST equalizer in the next generation of high-data-rate systems, development of a testbed and its validation through field tests is needed.

ST equalizers are classified into two types: simultaneous optimization and sequential optimization with adjustable weights for the antenna array and tap coefficients for the equalizers. The former type using MLSE is often called array-processing MLSE (AP-MLSE) [6], [7], and the latter is often referred to as a cascade connection of the antenna array processor and MLSE [1]–[5], [8]–[10]. The AP-MLSE provides better ISI reduction and space- and path-diversity gains [7], but its hardware is more complex. Thus, to determine the feasibility of applying the cascade-connection type in the near future, prototyping and field tests of cascade-connection ST equalizers have been done [8], [9], [11], [12].

We previously developed a testbed for evaluating cascade-connection ST equalizers for TDMA base station receivers and have shown the effectiveness of proposed ST equalizer [5] using a hardware fading simulator [11], [12]. We have now reached the final step in our research—the development of a field-test equipment for the ST equalizer and field measurements made within micro- and macrocell environments in the central Tokyo area. Unlike previously reported field tests [8], [9], we simultaneously measured in real time the instantaneous bit error rates (BERs) of the ST equalizer and a single array processor separately, as well as the received power and delay profile, while the mobile transmitter was driven.

Delay diversity transmission (DDT) creates delay paths and provides sufficient path diversity at the MLSE for flat-fading and small-delay-spread conditions. The application of DDT was investigated in previous works [13], [14] for a downlink case in which a base station had multiple transmitting antennas to enable the DDT to provide path diversity for the MLSE in a mobile station with a single receiving antenna, assuming independent flat Rayleigh fading. In contrast, we have now used...
DDT for the mobile transmitter uplink to provide path diversity for the MLSE in the ST equalizer at the base station. In the personal handyphone system (PHS), the major cordless phone system in Japan, many base station antennas in the central city area are placed on utility poles that are lower than the surrounding buildings. We showed that DDT is effective under a similar condition—the delay spread small enough in a PHS microcell uplink environment for DDT not to adversely affect the ST equalizer performance.

This paper is organized as follows. In Section II, the field-trial system is described. In Section III, the bit error characteristics against the delay spread and delay profile are discussed. In Section IV, the BER performance is discussed. In Section V, the field-test results are compared and discussed with the previous theoretical, simulation, and indoor test results. In Section VI, conclusions are summarized.

II. FIELD-TRIAL SYSTEM

Fig. 1 is a schematic illustration of the field-trial system, and Table I shows the system specifications. We measured received signal power at each antenna, in the intermediate-frequency (IF) band by using a logarithmic amplifier (log-amp) in each antenna branch. The simultaneously detected bit errors for the single array processor and the proposed ST equalizer and the power delay profile averaged over the antenna branches were stored in real time into a personal computer via a data logger. The array processors used sample-matrix-inversion-based algorithms. The proposed ST equalizer was a cascade connection of constrained array processors and a branch-metric-combining (BMC) MLSE unit designed to obtain both space- and path-diversity gains from first-arrival and one-symbol (1Ts)-delay paths while suppressing excessive ISI. The configurations and algorithms for the array processor and the ST equalizer are described in [5] and [11].

A four-dipole uniform circular array with a $4\sqrt{2}\lambda$ radius ($\lambda$: wavelength) is a typical antenna array configuration for a PHS base station in the central area of a city. Less than $0.5\lambda$ is generally assumed to be enough antenna spacing for a mobile to obtain sufficiently low fading correlation for diversity for a high-altitude base station antenna in a macrocell environment. However, we set the antenna spacing for the DDT at the mobile transmitter to $5\lambda$ and $15\lambda$, which are not feasible for a mobile terminal, because the DDT was conducted for a low-altitude base station antenna in a microcell environment in which antenna spacing sufficient to provide low fading correlation was uncertain. To focus on the ST equalization performance without regard to the fading correlation between DDT antennas, we used $15\lambda$ for the antenna spacing, which resulted in a sufficiently low correlation (Section IV).

Rubidium oscillators were used as local in the transmitter and receiver. Their radio frequency stability was within $3 \times 10^{-11}/s$ (0.00003 ppm) and thus radio frequency offset between them was negligible over the frame synchronization period (8 ms), which corresponded to a frequency stability of 0.037 ppm. If lower cost oscillators had been used instead, an auto frequency control (AFC) circuit would have been needed in the receiver to compensate for the frequency offset that could degrade system performance.

For the DDT at the mobile, the in-phase (I) and quadrature (Q) channel data were split, and the data in one channel were delayed in the baseband signal processing unit. The total power of the two transmitter antennas was made equal to the power of a single antenna without DDT by using an appropriate-length cable. Even when the DDT created delay paths beyond the equalization range of the MLSE, the antenna array presystem suppressed these paths and consequently prevented disruptive degradation in the MLSE.

Coding and interleaving effects strongly depend on random and burst errors due to variation speed in the channel relative to the burst length. Here, to clarify the effects of the ST equalizer, we did not include coding and interleaving and did not vary the burst length. However, it may be possible to surmise from the test results that burst errors appear only in the single array processor, not in the ST equalizer, or that the ST equalizer compensates for the burst errors against which coding and interleaving are not effective (Section III).
III. MEASUREMENT

A. Test Environments

Fig. 2 shows an overhead image of the three test environments, which were in the central Tokyo area [15]. The arrows indicate the array antenna locations. The solid and dotted lines indicate the courses of the mobile transmitter—which was driven in a counterclockwise direction (P1 → P2 → P3 → P4 → P1). It moved at an average speed of 20 km/h, so the Doppler frequency was about 60 Hz. Table II lists the heights of the antennas and of the surrounding buildings.

1) Test Environment 1: The array antenna was placed on the rooftop of a particularly tall building (70 m, twice as high as any other building in the area) about 600 m from the center of the course. This environment corresponds to a cell in an urban area for a TDMA personal digital cellular system—a second-generation cellular system still widely used in Japan.

2) Test Environment 2: The array antenna was placed on the rooftop of a seven-story building (25 m, about the same as other major buildings in the vicinity), about 300 m from the center of the course. This environment corresponds to a PHS cell for an urban area where PHS service has been enhanced by installing an array antenna at the base station.

3) Test Environment 3: The array antenna was raised to almost the same height as the utility poles (15 m), which were
TABLE II

<table>
<thead>
<tr>
<th>Antenna Setup</th>
<th>Test Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Height of Tx Antenna at Mobile Station</td>
<td>2 m</td>
</tr>
<tr>
<td>Height of Rx Array Antenna for ST Equalizer at Base Station</td>
<td>70 m</td>
</tr>
<tr>
<td>Height of Major Buildings Around Rx Antenna</td>
<td>30–35 m</td>
</tr>
<tr>
<td>Distance Between Tx and Rx Antennas</td>
<td>600 m</td>
</tr>
<tr>
<td>Observed Delay Spread</td>
<td>Large</td>
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</tbody>
</table>

Fig. 3. Delay spread, number of bit errors, and delay profile in each burst for test environment 1. (a) Delay spread and bit errors per burst. (b) Delay profile in each burst.

Fig. 4. Delay spread, number of bit errors, and delay profile in each burst for test environment 2. (a) Delay spread and bit errors per burst. (b) Delay profile in each burst.

lower than the height of the major buildings in the neighborhood (20–25 m). The distance between the transmitter and receiver was 20–100 m throughout the course. This environment also corresponds to a PHS cell for an urban area.

B. Bit Errors for the Single Array Processor and ST Equalizer With Delay Spread Variation

Figs. 3–6 show the measured results for test environments 1, 2, and 3 without DDT, and test environment 3 with 1Ts-DDT, respectively. In particular, they show the delay spread and delay profile averaged over the antenna branches and the number of bit errors for the single array processor and for the ST equalizer, measured in the first burst (125 $\mu$s) of each frame (8 ms) in real time as the mobile transmitter was driven through the course. The measurement resolution for the received power and delay profile was equal to the oversampling interval (0.061 $\mu$s). The delay spread ($\sigma$) was calculated using

$$\sigma = \sqrt{\frac{\sum_{k=0}^{K_{\text{max}}} (k - \tau_{\text{ave}})^2 p(k)}{\sum_{k=0}^{K_{\text{max}}} p(k)}}$$

(1)

where $k$ is the Nyquist sampling time (one-symbol duration)—i.e., $k = 0$ denotes the first-arrival signal timing—$\tau_{\text{max}}$
Fig. 5. Delay spread, number of bit errors, and delay profile in each burst for test environment 3. (a) Delay spread and bit errors per burst. (b) Delay profile in each burst.

Fig. 6. Delay spread, number of bit errors, and delay profile in each burst for test environment 3 with DDT. (a) Delay spread and bit errors per burst. (b) Delay profile in each burst.

Table III

<table>
<thead>
<tr>
<th>Test Environment</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>3 w/1Ts-DDT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.23</td>
<td>0.13</td>
<td>0.05</td>
<td>0.17</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.87</td>
<td>0.53</td>
<td>0.32</td>
<td>0.48</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.12</td>
<td>0.09</td>
<td>0.07</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Table III summarizes the delay characteristics for the test environments.

In test environments 1 and 2, the number of bit errors for the single array processor increased rapidly with the delay spread (Figs. 3 and 4); in contrast, the number for the ST equalizer remained low regardless of the delay spread. The delay spread was more than enough to provide the maximum diversity order at the ST equalizer, so DDT was not used. If DDT had been used instead, the number of excessive delay paths (delay time over 1Ts) would have increased. The ST equalizer would then have consumed degrees of freedom to suppress these paths and consequently decrease its diversity order as shown in [5] and [11]. The degree of BER degradation in the ST equalizer due to delay path dispersion created by the DDT has been estimated from the BER characteristics with the delay time difference shown in [11].

In test environment 3, the delay spread was too small to provide sufficient path diversity at the ST equalizer (Fig. 5). We then tried the 1Ts-DDT and the delay spread increased (Fig. 6). The number of bit errors for the single array processor increased with the delay spread because the single array could exploit only the first-arrival path while consuming degrees of freedom to suppress the created delay paths; it did not obtain any path-diversity gain from the delay paths. In contrast, the number of bit errors for the ST equalizer decreased. This was because the constrained array processors in each path-diversity branch did not use up any degrees of freedom with regard to the respective unconstrained desired paths; instead, they

is the maximum relative delay time, $p(k)$ is the power delay profile, and $\tau_{ave}$ is the average relative delay time

$$
\tau_{ave} = \frac{\sum_{k=0}^{K_{max}} \tau p(k)}{\sum_{k=0}^{K_{max}} p(k)}.
$$

(2)
suppressed the excessive delay paths. The MLSE then provided a path-diversity gain.

IV. BER PERFORMANCE

A. Definition of and How to Measure $E_b/N_0$

For each antenna branch, the energy of single bit ($E_b$) and the spectral noise density ($N_0$) were defined as $P_C/W_C$ and $P_N/W_N$, respectively, where $P_C$ was the received carrier power, $W_C$ was the occupied bandwidth of $P_C$, $P_N$ was the noise power, and $W_N$ was the bandwidth of $P_N$ in the D/C unit. The noise power was computed by first using Boltzmann’s equation and then adding the noise figure in the D/C unit. The received carrier power was computed by subtracting $P_N$ from the D/C unit output power measured using a power meter. We measured $W_C$ and $W_N$ at the D/C unit output with a spectrum analyzer. Beforehand, we connected the transmitter directly to the receiver for each antenna branch and measured the D/C unit output power and the log-amp output voltage with a voltage meter, while varying the transmit power. Taking into consideration the cable loss, we obtained a table for translating the output voltage of the log-amp into the $E_b/N_0$ of the received signal power. The table data were placed in the data logger, which transformed the incoming log-amp output into $E_b/N_0$ for all branches and averaged it over all branches. They were stored in real time in each frame along with the number of bit errors for the single array processor and for the ST equalizer.

B. BER Performance

We collected a sufficient amount of bit error data to ensure reliable BER performance in repeated measurements around the course while varying the transmit power from 0.0625 to 1 W. For each test environment, the bit errors and received power in each frame were gathered, sorted by $E_b/N_0$, and averaged over a 0.25-dB $E_b/N_0$ interval.

For test environments 1 and 2, we compared the BER performance of the ST equalizer to that of one without BMC and to that of the single array processor. For test environment 3, we also compared it to that of the ST equalizer with DDT.

As shown in Figs. 7 and 8, in test environments 1 and 2, respectively, the BER of the ST equalizer was better than that of the ST equalizer without BMC due to the path-diversity effect of BMC—the ST equalizer uses two separate sets of array weight vectors to respectively constrain the first-arrival and 1Ts-delay paths even when the fading correlation between signals on the branches is low. However, the diversity order of the ST equalizer was less than 1 and 2 in test environments 1 and 2, respectively, in part because it consumed much degrees of freedom to suppress many excessive long-delay paths. The BER of the ST equalizer was significantly better than that of the single array processor due to both array and path diversity effect. As shown in Fig. 9, in test environment 3, the DDT improved diversity order and consequently the BER of the ST equalizer. The diversity order of the ST equalizer and that of the ST equalizer with DDT was about 3–4. The slope of the BER curve with DDT was 1.2 times as steep as that without DDT. The ST equalizer and the ST equalizer with DDT worked well in the test environment 1 compared to other test environments. The improved BER with the ST equalizer also means reduction in the terminal transmit power by the transmit power control for uplink.
C. Envelope Correlation Between Antenna Branches

Fig. 10 shows the received signal envelope cross correlation of the antenna branches in test environments 1, 2, 3, and 3 with DDT. The values of the cross correlation include all combinations of the \( m \)th and \( n \)th branches \((m \neq n)\) calculated using

\[
\rho = \frac{E[ (e_m - \mu_{e_m})(e_n - \mu_{e_n})]}{(\sigma_{e_m}\sigma_{e_n})}
\]

(3)

where \( e_m \), \( \mu_{e_m} \), and \( \sigma_{e_m} \) are, respectively, the envelope, mean, and standard deviation of the received signal. Also, \( E[\cdot] \) is the ensemble average. These values were calculated every 225 frames (every 10 m at 20 km/h). An envelope cross correlation of 0.7 or less is generally considered sufficient for a satisfactory diversity-combining performance. About 80% of the envelope correlations were less than 0.7 in test environments 2 and 3; i.e., sufficient space diversity effect was obtained 80% of the time in these environments. In contrast, in test environment 1, only about 50% of the envelope cross correlations were below 0.7. This was because the receiving array antenna was placed on top of a particularly tall building about 600 m from the mobile terminal, so the angular spread of the arrival paths was narrow. A radius of \( 4\sqrt{2}\lambda \) for the circular array was not enough to obtain sufficient space diversity.

D. Envelope Correlation Between First-Arrival and 1Ts-Delay Paths

Fig. 11 shows the received signal envelope cross correlation of the first-arrival and 1Ts-delay paths, in test environment 3 and with 1Ts-DDT using \( 15\lambda \) antenna spacing. Although the 1Ts-DDT increased the correlation, 95% of the correlations were below 0.7 in test environments 2 and 3; i.e., sufficient space diversity effect was obtained 80% of the time in these environments. In contrast, in test environment 1, only about 50% of the envelope cross correlations were below 0.7. This was because the receiving array antenna was placed on top of a particularly tall building about 600 m from the mobile terminal, so the angular spread of the arrival paths was narrow. A radius of \( 4\sqrt{2}\lambda \) for the circular array was not enough to obtain sufficient space diversity.

V. COMPARISON AND DISCUSSION OF FIELD-TEST RESULTS WITH THEORETICAL AND INDOOR TEST RESULTS

We previously showed that the indoor test result of the field-test system using the hardware fading simulator was degraded Fig. 12. BER when transmit remained at the line-of-site (LOS) point in test environment 3.

by 1–4 dB compared with theoretical and simulation values due to hardware limitations of the analog section (e.g., the common AGC and the dynamic range of the A/D converter) [11, Fig. 10].

Fig. 12 shows field-test results for the one-branch, the array processor alone, and the ST equalizer experiments when the transmitter remained at the LOS in test environment 3. Theoretical curves for a static one-path model are also shown for comparison. Theoretical BER of the ST equalizer is the same as for the array processor alone, since both schemes can only exploit the static direct path and obtain four-branch array gain. The LOS environment in fact had multipath with short delay and slow fading caused by ambient objects (such as buildings, vehicles, and pedestrians) and was not equal to the static one-path model. The test result thus degraded compared with the theoretical curve and the degradation increased as the \( E_b/N_0 \) increased. The field-test result of the ST equalizer was better than that of the array processor alone because the BER of the ST equalizer degrade little when path delays were less than one symbol [11, Figs. 11 and 12].

For frequency-selective fading channel, the field-test results (Figs. 7–9) were measured when the transmitter moved through various LOS/NLOS conditions and arrival path condition varied
with time. Thus, the arrival path conditions in the test environments are not comparable with those in the hardware fading simulator for indoor test where path delays were fixed to multiples of the symbol period and average power of each path was equal. Hence, let us roughly compare the field result with the indoor test result in terms of diversity order. Diversity orders of the ST equalizer and the array processor alone in the indoor test [11, Fig. 10] were almost the same as those in the simulation [5, Fig. 6], i.e., $2(N - L + 2)$ and $N - L + 1$ respectively, where $N(= 4)$ was the number of the antenna branch and $L(= 2 - 6)$ was the number of arrival paths with fixed delay time and equal average power as previously mentioned. On the other hand, in the field-test result, the diversity orders of the array processor alone, the ST equalizer, and the ST equalizer with DDT were less than 2, 3, and 4, respectively, even in test environment 3 where the delay spread was extremely small. The major conceivable reason for the degradation, common to all test environments, was burst errors caused by symbol timing offset because the symbol synchronizer in the testbed was not tolerant of a long nonminimum phase condition in slow fading.

Our frame-and-symbol synchronizer captures the timing from the first-arrival path and uses the delay profile averaged over the antenna branches and temporally over some bursts to prevent the symbol timing offset. The indoor test validated our expected performance when the maximum Doppler frequency was more than 50 Hz [11, Figs. 8, 13, and 14]. During the field test, we have found that the symbol timing jitter increased when the maximum Doppler frequency was measured at several hertz by using the hardware fading simulator. Consequently, we assumed that the long nonminimum phase condition in slow fading caused the symbol timing offset in the symbol synchronizer and the BER of the ST equalizer and the array processor alone to be severely degraded. The BER degradation caused by the symbol timing offset can be overcome by using a fractionally spaced sample approach for the MLSE [16] and by introducing a fractionally spaced tapped delay line on each antenna branch [10].

The symbol timing offset can also be caused by radio frequency error between the transmitter and the receiver. We used the rubidium oscillators, and the frequency error did not have any effect on the symbol timing offset. For future commercial use, however, we have to consider the frequency offset caused by using a voltage-controlled crystal oscillator with the AFC circuit, instead of the rubidium oscillators. A joint AFC scheme across multiple branches would be helpful to combat the frequency offset [16].

VI. CONCLUSION

We tested an ST equalizer, which was a cascade connection of constrained array processors and BMC MLSE, for base station uplink for a TDMA mobile communication system in micro- and macrocell environments. DDT in mobile station was used in the microcell environment, in which delay spread was too small to provide sufficient path diversity at the ST equalizer. The ST equalizer provided a significantly better BER performance compared with a single array processor and with an ST equalizer without BMC in both environments. Using DDT in the microcell environment increased the delay spread and improved the diversity order and consequently the BER of the ST equalizer. The ST equalizer, with and without DDT, is suitable for such microcell environment. However, we found that the ST equalizer was not tolerant of symbol timing offset and requires improvements such as a fractionally spaced tapped delay line on each antenna branch and a fractionally spaced sample approach for the MLSE.

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