LETTER

Performance Evaluation of FTDL-Spatial/MLSE-Temporal Equalizers in the Presence of Co-channel Interference —Link-Level Simulation Results Using Field Measurement Data—

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SUMMARY Providing results of a series of link-level simulations for a class of spatial and temporal equalizer (S/T-equalizer) is the primary objective of this letter, which is supplemental to this letter's companion article. The S/T-equalizers discussed in this letter have a configuration that can be expressed as the cascaded connection of adaptive array antenna and maximum likelihood sequence estimator (MLSE): each of the adaptive array antenna elements has a fractionally spaced tapped delay line (FTDL), and the MLSE has taps covering a portion of the channel delay profile. Both the desired and interference signals suffer from severe inter-symbol interference (ISI). A major difference of this article from its companion letter is that account is taken of the presence of co-channel interference (CCI). Bit error rate (BER) performance of the S/T-equalizer is presented as a result of the link-level simulations that use field measurement data.
key words: *broadband mobile communication, adaptive array antenna, adaptive equalizer, spatial and temporal equalizer, field measurement data*

1. Introduction

Joint spatial and temporal equalization (S/T-equalization) techniques have been recognized as offering the potential to achieve a significant enhancement in signal transmission performance over broadband mobile communications channels. Various algorithms for S/T-equalizer signal processing have been proposed. Refs. [1] and [2] survey the historical backgrounds of known technologies, and summarize current trends in S/T-equalizer algorithm development. Despite the extensive effort put in to algorithm development, relatively few papers have described field performance results.

Initial investigation results on the effectiveness of spatial and temporal equalization (S/T-Equalization) techniques under real mobile radio propagation environments are presented in Refs. [3]–[6]. Their methodological basis is a link-level simulation using field measurement data for two-dimensional (spatial and temporal) channel sounding. Channel impulse response data, gathered through field measurements, were used to estimate the real performance of S/T-Equalizers. This paper's comparison letter [3] discusses the effects of using a maximum likelihood sequence estimator (MLSE), and then evaluates its performance sensitivity to symbol timing offset.

A primary objective of this letter is to present results of link-level simulations to supplement Ref. [3]'s results. The type of the S/T-equalizer investigated in this letter is the same as the one discussed in Ref. [3]: an L-element adaptive array antenna is followed by an MLSE; each of the L antenna elements is equipped with a fractionally spaced tapped delay line (FTDL). For the ease of notation, this S/T-Equalizer configuration is referred to as L-FTDL/MLSE hereafter.

The main purpose of S/T-Equalization is to endow receivers with immunity against co-channel interference (CCI) and intersymbol interference (ISI), aiming at allowing all users to use the same frequency- and time-slots (This situation is referred to as the $fu = 1$ condition henceforth, where fu denotes the frequency reuse factor). The difference between this letter and Ref. [3] is that this letter takes into account the presence of CCI: only one interferer is assumed in this letter, however it should be noted that the effect of more interference sources can be simulated in the same way. Results of field measurements conducted prior to the link-level simulations show that both the desired and interference signals suffer from severe ISI.

The link-level simulation itself is an off-line simulation, but makes it possible to compare system performances on a fair and practical basis since it uses the same field measurement data for S/T-equalizers having different parameter values. This letter evaluates the performance of the FTDL/MLSE S/T-Equalizer through link-level simulations using field measurement data gathered in an urban area of Tokyo. With the FTDL/MLSE configuration, the numbers of FTDL and MLSE taps are important design parameters.

This letter is organized as follows: Sect. 2 shows field measurement data that contain the temporal and spatial characteristics of the channels with desired

Manuscript received September 26, 2000.
Manuscript revised February 1, 2001.
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Table 1 Major specifications of field measurement and link-level simulations.

Bandwidth	100 MHz
Radio Frequency	5.2 GHz
Transmitter	Omnidirectional
Receiver	8-element ULA
Tx/Rx Synchronization	Rubidium Reference
Time-domain Resolution	6 nanosec.
Spatial-domain Resolution	2.5 deg.

and interference signals. Section 2 also describes the method this letter employs to simulate multiple users' communication environments. Section 3 describes the S/T-equalizer configuration investigated in this letter. Details of the link-level simulations are also presented. Section 4 then shows results of the simulations. The impact of changing the FTDL and MLSE tap numbers as well as the antenna element number is investigated.

2. Field Measurements

The field measurements conducted prior to the link-level simulations used the same two-dimensional channel sounder system as the one used in Ref. [3]. With this channel sounder system, whose major specifications are summarized in Table 1, it is possible to identify the channel impulse responses with sufficient accuracy to permit broadband signal transmission offline simulations.

The field measurement results are sets of data indicating the impulse responses of the radio channels established between the omnidirectional transmitter antenna and each of the L elements of the linear receiver antenna array. The test signal transmitted from the transmitter has a chirp waveform with 100-MHz bandwidth. The carrier frequency of the chirp signal is 5.2 GHz. The channel sounder employs FFT-based correlation processing at the receiver. A software program running on the channel sounder system provided two-dimensional (temporal and spatial) super-resolution signal analysis capability; it yielded 6 *nano*second time-domain resolution and 2.5 degree spatial-domain resolution.

A series of field measurements was conducted in a typical urban area of Tokyo prior to the link-level simulations. Two rounds of measurement took place at different times while keeping the receiver's position fixed: the transmitter was set up at Point A in the first run to simulate the desired user, and at Point B in the second run to simulate the interferer. (Points A and B are indicated in Fig. 1 showing geographical bearings of the measurement area). As indicated in Fig. 1, the $fu = 1$ condition was simulated by locating the interference user in an adjacent cell.

Figures 2(A) and (B) show examples of the two-dimensional profile of the received composite signal, as determined by space-time signal analysis: Fig. 2(A) is for Point A, and Fig. 2 (B) for Point B. Delay and

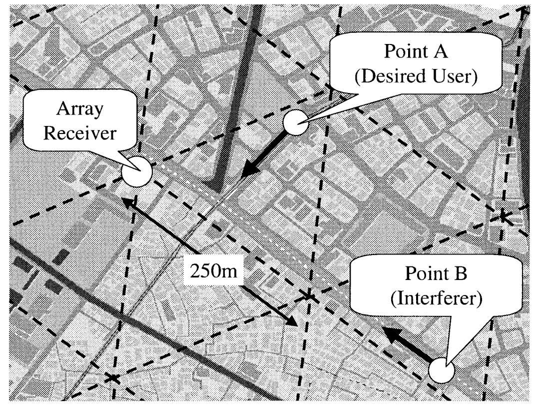
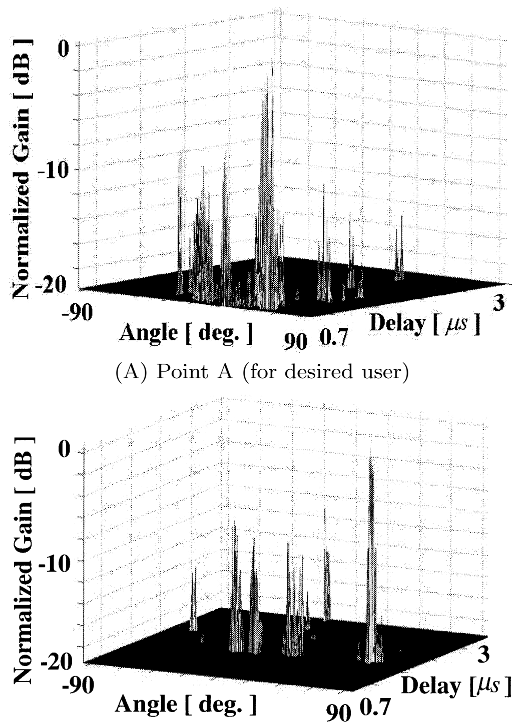


Fig. 1 Measurement environment.



(A) Point A (for desired user)

(B) Point B (for interferer)

Fig. 2 Example of measured delay-angular profile.

angle spreads at Point A are 460 *nano*seconds and 22.6 degrees, respectively. Those at Point B are 533 *nano*seconds and 18.2 degrees, respectively. The difference in sight angle between Points A and B from the receiver point is 57 degrees. Despite the 57 degree separation between the two transmitters', some of the signal components transmitted from Point A have direction-of-arrivals (DOAs) very close to those of the signal components transmitted from Point B.

3. Link-Level Simulations

3.1 S/T-Equalizer Configuration

Figure 3 shows a block diagram of the S/T-equalizer

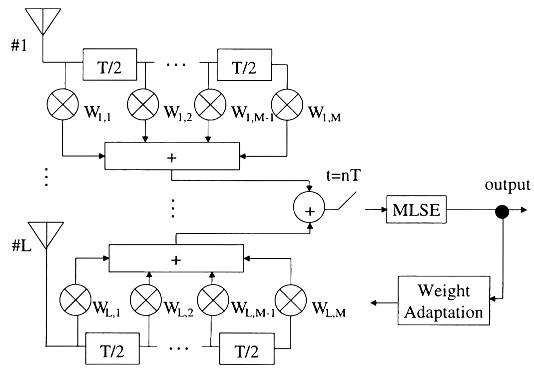


Fig. 3 Block diagram of S/T-equalizer.

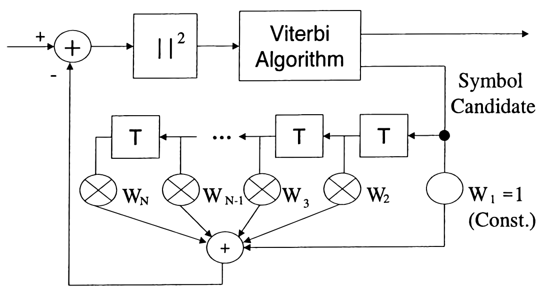


Fig. 4 Block diagram of MLSE.

evaluated in this letter. The key roles played by each part of Fig. 3's configuration are as follows. The adaptive array aims to suppress the interference components as well as the desired signal components having relatively large delays, while the MLSE equalizer aims to combine the desired signal components having small delays. Important parameters are the numbers of the antenna elements (L) and FTDL taps (M), which are expressed as (L, M) for notation convenience. Another important parameter is the number N of the feedback taps. Figure 4 shows a block diagram of the MLSE temporal equalizer, where N feedback taps are used to replicate the array output corresponding to the symbol sequence considered most likely to have been transmitted. The number of states used by the Viterbi algorithm for MLSE is $Q^{(N-1)}$ for Q-level signaling. For quaternary phase shifted keying (QPSK), $Q = 4$.

3.2 Simulation Details

Table 2 summarizes major specification of the signal format used in the link-level simulations. For both the desired and interference signals, QPSK was used as the modulation scheme. The symbol rate was set at 12 Msymbols/second, which should meet the requirement for initial studies of future broadband mobile communication systems. A Nyquist filter transfer function with rolloff-factor $\alpha = 0.5$ was shared equally by the transmitter and receiver. A 12 Mbps QPSK signal was root rolloff- filtered at both the transmitter and receiver for, respectively, spectrum shaping and noise reduction. All

Table 2 Major specifications of signal format.

Modulation	QPSK
Symbol Rate	12 Msym./sec.
Tx/Rx Filter	Roor Roll-off, $\alpha = 0.5$
Frame Format	Training: 450 Symbols Data Block: 4960 Guard Block: 40
Adaptive Array	L-element ULA M-tap $T/2$ spaced FFF
Adaptive Equalizer	16-state MLSE
Update Algorithm	RLS, $\lambda = 0.97$

$LM + N$ weights are updated by using the recursive least squares (RLS) algorithm at every symbol timing using the training sequence in the frames.

Two independent quaternary pseudo random (PN) sequences were generated: one was used as the desired user's information sequence to be transmitted, and the other as the interferer's. The root rolloff-filtered desired user's transmitted sequence was convolved with the impulse response data representing the multipath channel between Point A and each of the receiver' antenna elements. The interference signal was similarly processed. The received desired and interference signals, each scattered in time over a couple of microseconds due to the channel delay spread, are combined, and root rolloff-filtered. A white additive Gaussian noise (AWGN) sequence was added before root rolloff-filtering to simulate the correlation between the noise samples at the filter output. This process was done for each of the L antenna array elements.

A PC platform was used to perform all signal processing operations for link-level simulations, including calculating waveforms of root roll-off filtered symbol sequences to be transmitted, convolving the transmitted waveforms with the channel impulse response data, and further convolving the channel output with the root rolloff-filter's impulse response to obtain the output of the antenna elements.

At the transmitter sides, both desired and interference users were assumed to be synchronized with each other, but because of different propagation delays on the signals, which appear in the measured impulse response data, received symbols are no longer synchronized in terms of symbol timing. At the receiver, symbol timing was extracted from the desired signal's delay profile. In fact, optimal symbol timing should achieve the best signal transmission performance, but to the author's knowledge, no algorithms for optimal timing extraction that have reasonable complexity are known. In this letter, received symbol timing is defined as the timing at which the channel impulse response reaches its maximum magnitude.

For averaged performance evaluations, the simulation results obtained by using the channel impulse response data collected in the vicinity of the measurement location of interest have to be averaged. As shown in Fig. 5, channel impulse response data was collected

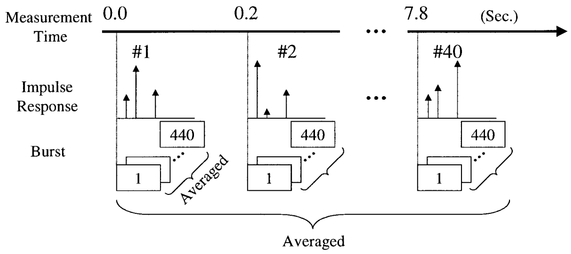


Fig. 5 Operation flow of simulation.

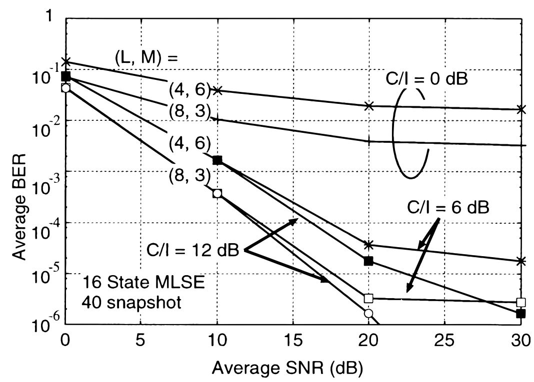


Fig. 6 Average BER vs. average received signal-to-noise ratio in dynamic condition.

every 1 meter in succession over 8 seconds of the test run for this purpose, resulting in 40 sets of data. In the link-level simulations, 440 bursts were transmitted for each of the 40 sets of the impulse response data, and the performance results for the 17600 (= 440 × 40) bursts were averaged. Assuming very slow fading compared to burst duration (454 microseconds = 0.2 seconds/440 bursts), the impulse response was fixed during each burst.

4. Results

Figure 6 shows average bit error rate (BER) performance curves with (L, M) and average signal-to-interference power ratio C/I as parameters. It is found that better BERs can be achieved with larger C/I values in the propagation environment characterized by Figs. 2(A) and (B). This suggests that the adaptive array part of the S/T-equalizer does not well suppress interference components. However, as noted in Sect. 2, some of the desired signal components transmitted from Point A have DOAs very close to those of the interference signal components transmitted from Point B. Interference components cannot be well suppressed by just the adaptive array antenna in such a situation.

It is also found from Fig. 5 that smaller BERs can be achieved by increasing the antenna element number L. Increasing FTDL tap number can also improve the BER performance. However, under the constraint that LM is a constant, it is more effective to allocate more taps to the spatial domain than to the time domain. An interpretation of this formula is that even in the case where the DOAs of some of the desired and interference components are very close, more interference components can be suppressed more by increasing the antenna element number, which produces more gain in the BER performance, rather than increasing FTDL tap number.

5. Conclusions

This paper has presented results of a series of link-level simulations using field measurement data, conducted to evaluate the performance of FTDL-Spatial/ MLSE-Temporal equalizers. Account was taken of the presence of CCI. The two-dimensional (spatial and temporal) profile of the received composite signal, obtained as a result of a preliminary analysis of the measurement data, reveals that both the desired and interference signals suffer from severe ISI, and that the DOAs with some of the desired and interference signal components were very close. It has been found that in such a situation, we should allocate more taps to the spatial domain than to the time domain, if the total number of taps has to be kept constant. More detailed system performance evaluations are left as future study.

Acknowledgement

The authors wish to thank Mr. Kazuaki Murota, senior vice president of NTT DoCoMo, Inc. for his encouragement during this research. The authors also wish to thank Mr. Yasuhiro Oda of NTT DoCoMo, Inc. for his support in conducting field measurement data.

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