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Effect of early stopping on error performance of iterative MIMO equalization: An experience in reality

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Abstract: Terminal-collaborated multiple-input multiple-output (MIMO) reception with adaptive terminal selection schemes has been studied experimentally. In the experimental system, frequency-domain iterative MIMO equalization was employed, and its performance was evaluated by making use of recorded signal waveforms in a measurement campaign. In iterative signal processing, it is known that early stopping can control unnecessary iterations. In this letter, it is revealed that early stopping can not only reduce computational complexity, but also improve the bit error ratio performance of iterative processing. This is because early stopping prevents the iteration process from causing errors.

Keywords: collaborative reception, distributed MIMO, terminal selection, early stopping, iterative equalization, measurement campaign

Classification: Wireless Communication Technologies

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1 Introduction

Terminal-collaborated multiple-input multiple-output (MIMO) reception has been studied [1, 2]. This is a form of distributed MIMO, in which a virtual terminal with a large number of reception antennas receives multiple data streams from a base station (BS). This virtual terminal consists of multiple mobile terminals (MSs) that are close to each other in order to share their received signals from the BS with other MSs. Terminal-collaborated MIMO reception does not require precoding, thereby is expected to achieve better performance in mobile environments than that of multi-user MIMO transmission with precoding.

The performance of this system can be improved with the increase of the number of collaborated MSs. However, the amount of power consumption and traffic overhead for inter-terminal collaboration will also be increased. In order to reduce these overhead, adaptive MS selection schemes that select an appropriate set of collaborated MSs have been proposed [3, 4, 5].

In this letter, early stopping (ES) [6] is applied to frequency-domain iterative MIMO equalization for this system. The only expected benefit of ES is reduction of computational complexity. However, it is revealed by a measurement campaign that ES can offer better bit error ratio (BER) performance.

2 System description

A BS transmits M spatially-multiplexed independent signal streams to N MSs on the same carrier frequency at the same time. On the receiver side, each MS equipped with a single antenna shares the received signals with other MSs. L MSs out of N candidate MSs are selected for terminal-collaborated MIMO reception. Let $\mathcal{L} \subseteq \mathcal{N}$ denote the set of selected MSs where $\mathcal{N}$ is the set of the candidate MSs.

2.1 Frequency-domain iterative equalization

Frequency-domain (FD) iterative equalization is applied to received signals [7]. This scheme combines three processes: i) MMSE frequency-domain equalization, ii) soft decoding of low-density parity-check code (LDPC) by belief propagation (BP), and iii) soft cancellation.

Let $\boldsymbol{y}_{\mathcal{L}}(k)$ be $[y_1(k), y_2(k), \ldots, y_L(k)]^{\mathrm{T}} \in \mathbb{C}^{L\times 1}$ where $y_l(k)$ is the received signal at the kth symbol of lth MS in $\mathcal{L}$. The frequency-domain received signals

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$\boldsymbol{Y}_{\mathcal{L}}(f) \in \mathbb{C}^{L\times 1}$ are equalized by a minimum mean square error (MMSE) filter. The equalized signals $\tilde{\boldsymbol{X}}(f) \in \mathbb{C}^{M\times 1}$ are converted to the signals $\tilde{\boldsymbol{x}}(k) \in \mathbb{C}^{M\times 1}$ in TD. Then, BP decoding calculates log likelihood ratios (LLRs) $L(c_{m,k,i})$ where $c_{m,k,i}$ is the ith bit of the kth symbol of the mth transmitted stream. In an FD soft replica generator, soft-decision symbols $\hat{\boldsymbol{x}}(k) = [\hat{x}_1(k), \hat{x}_2(k), \ldots, \hat{x}_M(k)]^{\mathrm{T}} \in \mathbb{C}^{M\times 1}$ are generated as follows in the case of quadrature phase-shift keying (QPSK) modulation:

$$\hat{x}_m(k) = \frac{1}{\sqrt{2}}\left(\tanh\left(L(c_{m,k,1})/2\right) + \tanh\left(L(c_{m,k,2})/2\right)\sqrt{-1}\right). \tag{1}$$

The symbols $\hat{\boldsymbol{x}}(k)$ are converted to signals $\hat{\boldsymbol{X}}(f) = [\hat{X}_1(f), \hat{X}_2(f), \ldots, \hat{X}_M(f)]^{\mathrm{T}} \in \mathbb{C}^{M\times 1}$ in FD. Next, soft-decision replicas $\hat{\boldsymbol{Y}}_{\mathcal{L},m}(f) \in \mathbb{C}^{L\times 1}$ are generated as follows:

$$\hat{\boldsymbol{Y}}_{\mathcal{L},m}(f) = \boldsymbol{g}_{\mathcal{L},m}(f)\hat{X}_m(f), \tag{2}$$

where $\boldsymbol{g}_{\mathcal{L},m}(f) \in \mathbb{C}^{L\times 1}$ is a channel transfer function.

Equalized signals by an MMSE filter with soft-cancellation can be expressed as

$$\tilde{X}_m(f) = \boldsymbol{w}^{\mathrm{H}}_{\mathcal{L},m}(f)\left\{\boldsymbol{Y}_{\mathcal{L}}(f) - \sum_{i\neq m}\hat{\boldsymbol{Y}}_{\mathcal{L},i}(f)\right\}, \tag{3}$$

where $\boldsymbol{w}_{\mathcal{L},m}(f) \in \mathbb{C}^{L\times 1}$ is an MMSE filter with a priori information. This filter utilizes residual error coefficients $\beta_m (0 \leq \beta_m \leq 1)$ shown below [7]

$$\beta_m = \begin{cases} 0, & \text{all the parity-check equations are satisfied} \\ 1 - \frac{1}{K}\sum_k |\hat{x}_m(k)|^2, & \text{otherwise,} \end{cases} \tag{4}$$

where K is the number of data symbols. As shown in this equation, if all the parity-check equations of the mth stream are satisfied for hard decisions formed on the a posteriori LLRs, let β_m be 0. These three processes are repeated up to Q times as an outer loop.

2.2 MS selection

Three MS selection schemes are considered. In a maximum product of singular values (MPoSV) MS selection scheme [3], L MSs are selected frame by frame based on the singular values of the estimated channel matrix. The following two schemes assume BER information available at the receiver. Therefore, their performance is studied for comparison purpose. In a fixed MS selection scheme (denoted as Fixed), L MSs are selected and remain unchanged. We focus on the best selection pattern $\mathcal{L}^*_q$ in terms of average BER, which can be given by

$$\mathcal{L}^*_q = \arg\min_{\mathcal{L}\subseteq N}\sum_j p(j, \mathcal{L}, q), \tag{5}$$

where $p(j, \mathcal{L}, q)$ is the BER averaged over all streams at the qth outer iteration in the jth frame. In a perfect MS selection scheme (denoted as Perfect), the best L MSs are selected frame by frame among $\binom{N}{L}$ selection patterns in terms of BER. The selected MSs can be given by

$$\mathcal{L}^*_{j,q} = \arg\min_{\mathcal{L}\subseteq N} p(j, \mathcal{L}, q). \tag{6}$$

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2.3 Stopping criterion

The residual error coefficients shown in Eq. (4) are employed as a stopping criterion of ES. The outer loop is repeated until the following inequality holds or until the maximum number of outer iterations is reached.

$$\sum_{m=1}^{M} \beta_m \leq \varepsilon \tag{7}$$

By adjusting the iteration control threshold ε, the number of iterations q can be reduced. The BER performance with ES is denoted as $p_{\mathrm{ES}}(j, \mathcal{L}, Q)$, where Q is the maximum number of iterations.

In Fixed with ES, the BER $p_{\mathrm{ES}}(j, \mathcal{L}, Q)$ is used instead of $p(j, \mathcal{L}, q)$ in Eq. (5). In Perfect with ES, we jointly optimize $\mathcal{L}$ and q as follows:

$$\mathcal{L}^{*}_{j,Q} = \arg \min_{\substack{\mathcal{L} \subseteq \mathcal{N} \\ 1 \leq q \leq Q}} p(j, \mathcal{L}, q). \tag{8}$$

3 Experimental setup

Four transmit antennas ($M = 4$) were arranged in 3.8 m×2.5 m square-shape as shown in Fig. 1 (a). Each transmit antennas was a horizontal-plane omnidirectional vertical antenna (5.8 dBi) and mounted on the roof of a building in Kyoto University at 25.5 m above the ground. The BS transmitted spatially multiplexed packets by QPSK modulation every 50 ms frame. The transmit power was 1 W per antenna, the carrier frequency was 427.2 MHz, and the symbol rate was 312.5 kilo symbols per second.

Six receive antennas ($|\mathcal{N}| = N = 6$) were arranged in a uniform circular array as shown in Fig. 1 (b). Each receive antenna was a 2.15 dBi quarter-wave and horizontal-plane omnidirectional monopole antenna and mounted on the roof of a vehicle (2.1 m height). A subset $\mathcal{L}$ ($|\mathcal{L}| = L = 4$) was selected from six received signals and used for equalization/demodulation. In order to examine BERs of all

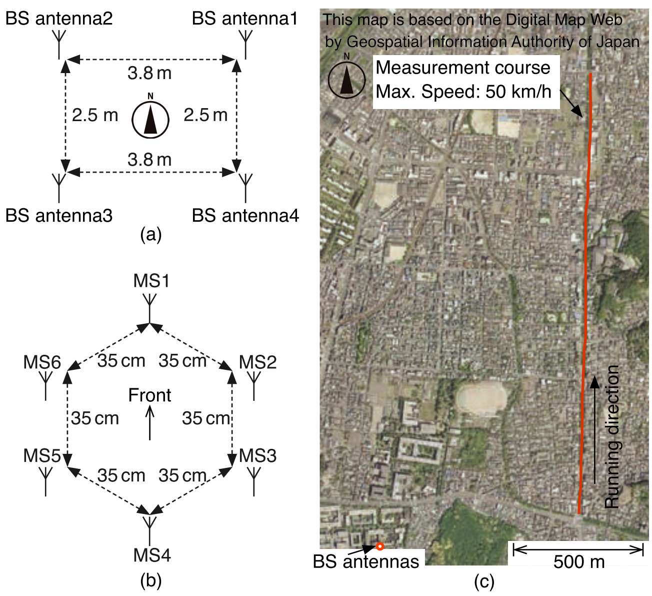

Fig. 1. BS and MS antennas, and measurement course.

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possible signal combinations, received signal waveforms from the BS were recorded at each MS and used for offline processing. Therefore, there was no inter-MS communication for collaboration in this letter.

The packet included a synchronization word of 15 symbols, a training sequence of 39 symbols, a control word of 15 symbols, a cyclic prefix of four symbols, and a data sequence of 192 symbols. Timings and frequencies of the entire system were based on 1-pulse-per-second signals and 10 MHz signals of global positioning system receivers.

We drove the vehicle twice along Shirakawa-dori Street, Sakyo-ku, Kyoto, heading north as shown in Fig. 1 (c). In this driving course, the average received power was greater than −80 dBm. The received signals while the vehicle stopped at traffic lights were not used in offline processing.

The noise variance for the MMSE filter and the LPDC decoder was optimized according to the average BER without ES. The number of iterations of the inner loop (BP) and the outer loop were eight and $Q = 3$, respectively.

4 Experimental results

The BER performance of iterative MIMO equalization with and without ES was evaluated by making use of the recorded signals. The iteration control threshold ϵ for ES was determined based on the average BER over the entire course.

Empirical cumulative distribution functions (CDF) of BER averaged over four streams in a frame are shown in Fig. 2. Note that absolute values of empirical CDFs are different between two trials due to different traffic conditions (e.g. vehicle speed, lane position, other vehicles). In Fixed, the best performance among those of 15 selection patterns is shown.

The BER performance of all three MS selection schemes was improved by ES as shown in Fig. 2. These improvements were confirmed in both of the two trials. Table I shows the average number of iterations and the average BER performance. As shown in this table, the BER performance without ES was improved by increasing q. Interestingly, ES can offer better average BERs with much smaller average q. This is because ES can control unnecessary iterations leading to catastrophic error propagation.

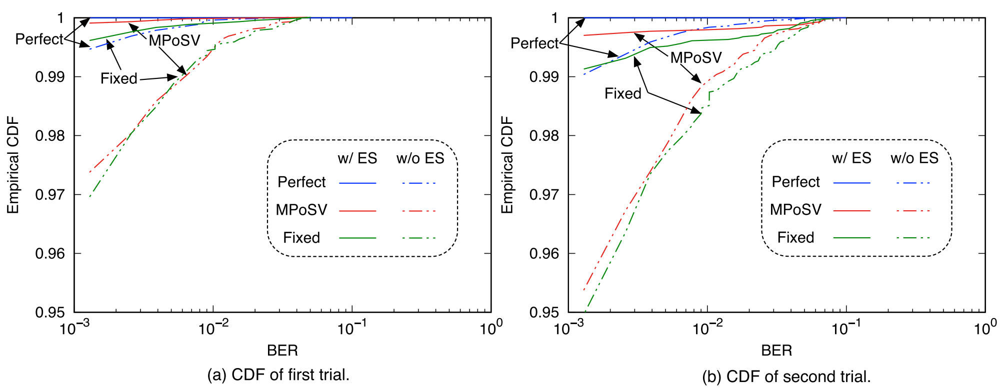

Fig. 2. Empirical CDF of BER. (a) First trial. (b) Second trial.

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Table I. Comparisons of average number of iterations and BER performance.

(a) First trial.

Scheme		$q=1$	$q=2$	$q=3$	ES
Perfect	Avg. q	1	2	3	1.01
	Avg. BER	1.4×10^{-4}	6.1×10^{-5}	4.4×10^{-5}	0.0
MPoSV	Avg. q	1	2	3	1.04
	Avg. BER	8.5×10^{-4}	3.2×10^{-4}	2.5×10^{-4}	1.6×10^{-5}
Fixed	Avg. q	1	2	3	1.15
(Best)	Avg. BER	3.4×10^{-3}	3.4×10^{-4}	2.7×10^{-4}	5.0×10^{-5}

(b) Second trial.

Scheme		$q=1$	$q=2$	$q=3$	ES
Perfect	Avg. q	1	2	3	1.02
	Avg. BER	3.1×10^{-4}	1.2×10^{-4}	9.4×10^{-5}	6.6×10^{-6}
MPoSV	Avg. q	1	2	3	1.07
	Avg. BER	1.3×10^{-3}	6.3×10^{-4}	5.1×10^{-4}	1.1×10^{-4}
Fixed	Avg. q	1	2	3	1.22
(Best)	Avg. BER	5.5×10^{-3}	7.5×10^{-4}	6.2×10^{-4}	1.9×10^{-4}

ES by parity-check equations (not β_m) can offer almost the same but slightly degraded BER performance and increased average q in this measurement campaign. Note that ES can reduce the errors that cannot be avoided even by Perfect.

5 Conclusion

This letter has presented an effect of ES on the error performance of iterative MIMO equalization. By using ES, the average number of iterations was reduced significantly. Moreover, it is shown that the BER performance was also improved. This is beyond our expectations, and currently under investigation. The results thus far suggested that a possible cause was phase rotation in a packet.

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