Performance Evaluation of a Space-Time Turbo Equalizer in Frequency Selective MIMO Channels Using Field Measurement Data

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Abstract— **Evaluating in-field performances of our proposed MIMO Turbo equalizer, Soft Canceller (SC) followed by MMSE (SC/MMSE) Space-Time (S/T) MIMO Turbo Equalizer, is the primary objective of this paper. The SC/MMSE S/T MIMO Turbo MIMO Turbo equalizer discussed in this paper performs joint MIMO channel estimation, SC/MMSE MIMO signal detection, and decoding of the channel code used, all in an iterative manner. Full diversity gain can be achieved with practical computational complexity in the presence of rich scattering in space and time domains in MIMO communication environments. A series of field measurement campaign took place in an urban area of Tokyo using a channel sounder system, and sets of collected channel impulse response data were used in off-line simulations to evaluate in-field performances of the MIMO Turbo equalizer. In 2-users 2-receive antenna MIMO uplink environments, bit error rate performances were evaluated for the two simultaneous users. Results of the simulations are presented in this paper.**

I. Introduction

Post third-generation (3G) broadband mobile communication systems will be required to transmit more than 100 Mbps signals to as many users as possible within a finite frequency bandwidth available. This requirement leads to an ultimate goal of wireless communication engineering, where all user use the same time- and frequency-slots without spreading their signals in the frequency domain. The Multiple -Input and Multiple-Output (MIMO) communication system concept has been considered as a conceptual and technological basis that can achieve this ultimate goal.

Recent studies revealed great potential of the MIMO communication systems. Capacity analysis [1] and signal separation algorithm development [2] are two major research themes. Since MIMO communication system performances fully depend on channel characteristics such as spatial- and temporal- scattering of received signals, performance evaluation in real propagation environments is of greater importance than in the 3G and its prior systems.

Despite the volume of papers [4] describing the MIMO channel capacity supported by field measurement data, few has dealt with performances of MIMO signal separation algorithms in real fields. This paper evaluates using field measurement data performances of our proposed MIMO Turbo equalizer, Soft Canceller (SC) followed by MMSE (SC/MMSE) Space-Time (S/T) MIMO Turbo Equalizer [3], in frequency selective MIMO channels. Our proposed MIMO Turbo equalizer, which is an extension of Wang and Reynolds's iterative equalizer [5], performs joint MIMO channel estimation, SC/MMSE MIMO signal detection, and decoding, all in an iterative manner. The SC/MMSE signal detector consists of a soft interference canceller and an MMSE adaptive filter that are cascaded to achieve drastic computational complexity reduction from the conventional trellis-based optimum signal detectors. Since the iterative channel estimator re-estimates channel parameters at every iteration by using as signal reference both hard decision results of code bits and unique word sequence of each transmitter, accurate channel estimates can be obtained after reasonable times of iterations, even if relatively short unique word sequences are available.

Performances of the proposed MIMO Turbo equalizer were evaluated through off-line computer simulations. Channel impulse response data was gathered in a typical urban area of Tokyo, and sets of the collected data were used to simulate uplink asynchronous 2-user 2-receive antenna MIMO channel. Results of the simulations verify the effectiveness of the iterative channel estimation technique and that the SC/MMSE S/T MIMO Turbo equalizer can properly separate two moving users signals. This paper is organized as follows: Section II describes the wideband MIMO channel model used in this paper. A mathematical Space-Time representation of the MIMO channel is given. Section III presents our proposed SC/MMSE S/T MIMO Turbo equalization algorithm. Section IV describes in detail the iterative channel estimation technique. Section V briefly introduces the field measurement campaign conducted to collect sets of the channel impulse response data in the field. Section VI shows results of computer simulations conducted to verify the effectiveness of the proposed algorithm in the field.

II. MIMO Channel Model

Figure 1 shows a wideband MIMO channel model; there are N users, and the receiver is equipped with M antennas. All N users transmit information symbols using the same time- and frequency-slots without spreading their signals in the frequency domain. This paper assumes a

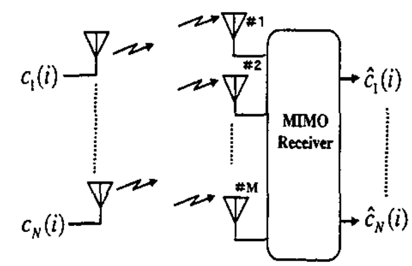

Fig. 1. MIMO Channel Model

coded MIMO system as shown in Fig. 2. The information symbols $c_n(i)$s are first encoded by each user's channel encoder where i and n denotes the symbol and user indices, respectively. The coded symbols are then interleaved and modulated according to the modulation format used. The modulated symbols $b_n(k)s$ are then transmitted over frequency selective fading channels. k denotes the index of modulated symbols. At the receiver, discrete time measurement at the m-th antenna yields the sample series $r_m(k)$ of the antenna output as

$$r_m(k) = \sum_{l=0}^{L-1} \sum_{n=1}^{N} h_{mn}(l) b_n(k-l) + v_m(k), \qquad (1)$$

where L is the channel memory length[1]. Without loss of generality, the channel memory length is assumed to be identical for all N users. $h_{mn}(l)$ is a discrete time representation of the channel between the n-th user and the m-th receiver antenna, and $v_m(k)$ is additive white Gaussian noise (AWGN).

Stacking those measurements into a vector which is equivalent to sampling in the space domain, results in

$$\begin{aligned} r(k) &\equiv [r_1(k), r_2(k) \dots r_M(k)]^T \qquad (2) \\ &= \sum_{l=0}^{L-1} H(l) b(k-l) + v(k), \qquad (3) \end{aligned}$$

where

$$H(l) = \begin{bmatrix} h_{11}(l) & \dots & h_{1N}(l) \\ \vdots & \ddots & \vdots \\ h_{M1}(l) & \dots & h_{MN}(l) \end{bmatrix}, \qquad (4)$$

$$b(k-l) = [b_1(k-l), b_2(k-l) \dots b_N(k-l)]^T, \quad (5)$$

[1] Equation (1) is valid regardless of the synchronization in symbol timing among the users. In fact, impulse responses of the channel and filters in the transmitter and the receiver can be folded into $h_{mn}(l)$. See [5].

and

$$v(k) = [v_1(k), v_2(k) \dots v_M(k)]^T. \qquad (6)$$

Finally, temporal sampling takes place to capture the multipath signals for diversity combining, yielding the following space-time representation of the received signal $y(k)$

$$\begin{aligned} y(k) &\equiv [r^T(k+L-1), r^T(k+L-2) \dots r^T(k)]^T \qquad (7) \\ &= H \cdot u(k) + n(k), \qquad (8) \end{aligned}$$

where

$$H = \begin{bmatrix} H(0) & \dots & H(L-1) & & O \\ & \ddots & & \ddots & \\ O & & H(0) & \dots & H(L-1) \end{bmatrix} \qquad (9)$$

is the channel matrix with $u(k)$ and $n(k)$ being

$$u(k) = [b^T(k+L-1) \dots b^T(k) \dots b^T(k-L+1)]^T \qquad (10)$$

and

$$n(k) = [v^T(k+L-1) \dots v^T(k) \dots v^T(k-L+1)]^T, \qquad (11)$$

respectively.

III. SC/MMSE S/T MIMO Turbo Equalization Algorithm

A. System Model

Figure 2 shows a block diagram of the SC/MMSE S/T MIMO Turbo equalizer. The equalizer is comprised of a SC/MMSE detector and SISO channel decoders. Binary Phase-Shift Keying (BPSK) is assumed in this paper as a modulation scheme used. The detector produces the Log Likelihood Ratio (LLR) for each coded bit as

$$\begin{aligned} \Lambda_1[b_n(k)] &= \log \frac{Pr[b_n(k) = +1 | y(k)]}{Pr[b_n(k) = -1 | y(k)]} \qquad (12) \\ &\equiv \lambda_1[b_n(k)] + \lambda_2^p[b_n(k)], \qquad (13) \end{aligned}$$

where $\lambda_1[b_n(k)]$ is the extrinsic information fed to the n-th user's channel decoder following the MMSE detector, and $\lambda_2^p[b_n(k)]$ is the *a priori* information provided by the n-th user's channel decoder.

The channel decoders derive the LLR for each coded bit as

$$\begin{aligned} \Lambda_2[b_n(j)] &= \log \frac{Pr[b_n(j) = +1 | \lambda_1[b_n(j)], j = 0, \dots, B-1]}{Pr[b_n(j) = -1 | \lambda_1[b_n(j)], j = 0, \dots, B-1]} \qquad (14) \\ &\equiv \lambda_2[b_n(j)] + \lambda_1^p[b_n(j)], \qquad (15) \end{aligned}$$

where, with j being symbol index after de-interleaving, $\lambda_2[b_n(j)]$ is the extrinsic information fed back to the MMSE detector, and $\lambda_1^p[b_n(j)]$ is the *a priori* information provided by the channel detector. B is the burst length.

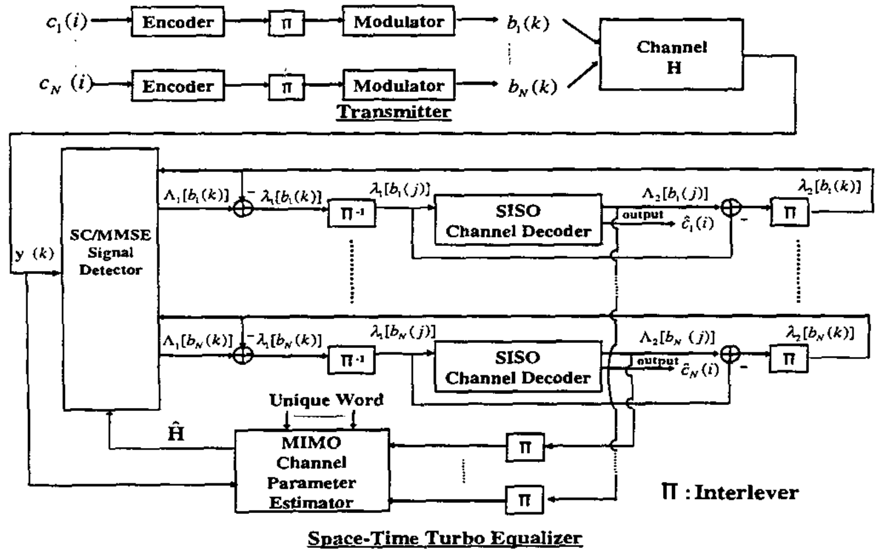

Fig. 2. System Model

After sufficient times of iterations, estimates of each user's information symbol can be obtained as

$$\hat{c}_n(i) = sign(\Lambda_2[c_n(i)]) \quad (n = 1, ..., N) \tag{16}$$

where

$$\Lambda_2[c_n(i)] = \log \frac{Pr[c_n(i) = +1|\lambda_1[b_n(j)], j = 0, ..., B-1]}{Pr[c_n(i) = -1|\lambda_1[b_n(j)], j = 0, .., B-1]}. \tag{17}$$

B. SC/MMSE Signal Detector

A block diagram of the SC/MMSE signal detector is shown in Fig.3. The detector consists of N independent detectors. In the following, we assume the 1-st user is the user of interest. The same algorithm should apply to signal detection of the other $N-1$ users. Utilizing the extrinsic information provided by the n-th user's channel decoder, the MMSE detector first forms soft estimates of all N users' k-th symbol as

$$\tilde{b}_n(k) = tanh[\frac{\lambda_2[b_n(k)]}{2}] \quad (n = 1, ..., N) \tag{18}$$

which are used to form the *soft replica* $\boldsymbol{H} \cdot \tilde{\boldsymbol{u}}(k)$ of the Multiple Access Interference (MAI) caused by interferers' signal components and Inter Symbol Interference (ISI) caused by the desired user's delayed signal components. The *soft replica* is subtracted from the received signal vector $\boldsymbol{y}(k)$ to produce the 1-st user's signal estimate vector as

$$\tilde{\boldsymbol{y}}_1(k) = \boldsymbol{y}(k) - \boldsymbol{H} \cdot \tilde{\boldsymbol{u}}_1(k), \tag{19}$$

where

$$\tilde{\boldsymbol{u}}_1(k) \equiv [\tilde{\boldsymbol{b}}^T(k+L-1) \ldots \tilde{\boldsymbol{b}}^T(k) \ldots \tilde{\boldsymbol{b}}^T(k-L+1)]^T \tag{20}$$

with

$$\tilde{\boldsymbol{b}}(k+l) = [\tilde{b}_1(k+l) \ldots \tilde{b}_N(k+l)]^T. \tag{21}$$

If $l = 0$,

$$\tilde{\boldsymbol{b}}(k) = [0, \tilde{b}_2(k) \ldots \tilde{b}_N(k)]^T \tag{22}$$

with the 1-st element being zero. Equation (19) yields *soft interference cancellation*.

The objective of the rest of the algorithm is to suppress the ISI and MAI residuals left after the *soft interference cancellation*. An adaptive linear filter is used for this purpose: the $M \times L$-vector $\boldsymbol{w}_1(k)$ of the filter taps is determined so that the Mean Squared Error (MSE) between the filter output and the signal point corresponding to the detected user's symbol is minimized as

$$\boldsymbol{w}_1(k) = arg \min_{\boldsymbol{w}_1(k)} \|\boldsymbol{w}_1^H(k)\tilde{\boldsymbol{y}}_1(k) - b_1(k)\|^2. \tag{23}$$

Since the derivation of the optimum vector $\boldsymbol{w}_1(k)$ follows [1], only the results are shown below:

$$\boldsymbol{w}_1(k) = [\boldsymbol{H}\boldsymbol{\Lambda}_1(k)\boldsymbol{H}^H + \sigma^2\boldsymbol{I}]^{-1}\boldsymbol{h}_1, \tag{24}$$

where

$$\boldsymbol{h}_1 \equiv [h_{11}(L-1)...h_{M1}(L-1)...h_{11}(0)...h_{M1}(0)]^T \tag{25}$$

and

$$\boldsymbol{\Lambda}_1(k) = diag[\boldsymbol{D}(k+L-1)...\boldsymbol{D}(k)...\boldsymbol{D}(k-L+1)] \tag{26}$$

with

$$\boldsymbol{D}(k+l) = diag[1-\tilde{b}_1^2(k+l)...1-\tilde{b}_n^2(k+l)...1-\tilde{b}_N^2(k+l)]. \tag{27}$$

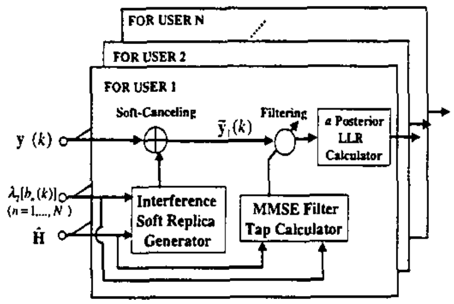

Fig. 3. SC/MMSE Signal Detector

For $l = 0$,

$$D(k) = diag[1, 1 - \tilde{b}_2^2(k), ..., 1 - \tilde{b}_N^2(k)] \quad (28)$$

with the (1,1)-element being one. By approximating error at the MMSE filter output by a Gaussian process [1], the extrinsic information of the 1-st user to be delivered to the channel decoder can be derived as,

$$\lambda_1[b_1(k)] = \log \frac{Pr[y(k)|b_1(k) = +1]}{Pr[y(k)|b_1(k) = -1]} \quad (29)$$

$$= \frac{4Re[z_1(k)]}{1 - \mu_1(k)}, \quad (30)$$

where $z_1(k)$ is the filter output

$$z_1(k) = w_1^H(k)\tilde{y}_1(k), \quad (31)$$

and

$$\mu_1(k) = h_1^H[HA_1(k)H^H + \sigma^2 I]^{-1} h_1. \quad (32)$$

IV. Iterative Channel Estimation

The sensitivity of Turbo equalization performance to channel estimation error was reported in [6]. It is obvious that increasing the accuracy of channel estimation enhances the performance. In deriving the algorithm described in Section III, all elements of channel matrix **H** were assumed to be known. This section proposes a new channel estimation scheme that effectively utilizes the iterative mechanism of the MIMO Turbo equalizer.

It is assumed that each of the N users' information sequences is headed by a unique word sequence whose waveform and timing are known to the receiver. Prior to the first iteration for the MIMO equalization, the N users' channel impulse responses are estimated by using the unique word sequences as signal references. The Recursive Least Square (RLS) algorithm may be used to estimate the N users' channel impulse responses. Initial estimates of the N users' channel impulse responses are obtained at the end of the unique word period. The receiver then runs the first iteration of the MIMO equalization algorithm described in Section III. The first iteration produces initial soft estimates of the N users' transmitted symbols given by

$$\tilde{b}_n(k) = tanh[\frac{\Lambda_2[b_n(k)]}{2}]. \quad (n = 1, ..., N) \quad (33)$$

Obviously, the larger the $|\tilde{b}_n(k)|$'s value, the more reliable it is, which suggests that the hard decisions of $\tilde{b}_n(k)$s' having relatively large $|\tilde{b}_n(k)|$ values can be used as additional signal references for channel estimation. Thresholding may properly identify the reliable soft estimates. Additional signal references are then given as signal points corresponding to the hard decision results for the symbols identified as being reliable.

Prior to the second iteration, the RLS parameter estimation algorithm is run again using as signal references both the unique word waveform and the information symbols identified as being reliable. The estimates of the channel impulse responses are then updated. The receiver runs the second iteration for the MIMO equalization using the updated channel estimates. This process is repeated. Because of the Turbo principle, the $|\tilde{b}_n(k)|$ values increase with the iteration number, thereby yielding more additional reference signals. This results in better estimates of the channel impulse responses.

V. Field Measurement

Two sets of a commercially available channel sounder system [7] were used in the field measurement. Heights of two omnidirectional and receive antennas of the sounders were 40m and 46m from the ground. The output of the field measurement is a set of data indicating the impulse responses of the radio channels between transmitter's omnidirectional antenna and each of the two omnidirectional receive antennas at the base station. The test signal transmitted from the transmitter was a chirp signal with a 100-MHz bandwidth. The carrier frequency was 5.2 GHz. The field measurement took place in a typical urban area of Tokyo.

VI. Simulation Results

This section presents results of computer simulations conducted to evaluate performances of the MIMO Turbo equalizer. BPSK was used as a modulation scheme. The symbol rate was set at 12M symbols/second. Transfer function of a Nyquist filter with roll-off factor = 0.5 was shared equally by the transmitter and receiver. A rate 1/2 non-systematic convolutional code with the constraint length of 3 and generators $[G_1, G_2] = [5, 7]_{oct}$ was used. A 12 Mbps BPSK signal was root roll-off filtered at both the transmitter and receiver for spectrum shaping and noise reduction, respectively. One burst has 900 coded symbols, headed by a 100-symbol unique word sequence for channel estimation. The Recursive Least Squares (RLS) algorithm was used to estimate the impulse responses by using the training sequence embedded periodically in the transmitted data frames. The threshold value for iterative channel estimation was set at 0.5. A random interleaver was assumed. The size of the interleaver is same as the frame length. The Max-Log-MAP algorithm was used in the SISO channel decoders. Signal processing for the simulations, including calculating waveforms of root rolloff-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, was all conducted on a PC platform.

A. BER performances of two static users

Two data points A and B shown in Fig. 4 were chosen for the 1st user and the 2nd user, respectively. Figures 5-(a) and -(b) show BER performances of the 1st and the 2nd user, respectively, where the channel matrix **H** was estimated only once in the first iteration by using the unique word sequences. Figures 6-(a) and -(b) show BER performances of the 1st and the 2nd user, respectively, where the iterative channel estimation was performed. The results show the iterative channel estimation can achieve more accurate estimate of **H**, and thereby better BER performances.

B. BER performances of two moving users

Two data points C and D shown in Fig. 4 were chosen for the 1st user and the 2nd user, respectively. Two sets of impulse response data collected over 8 seconds of measurement run at each point were used to simulate uplink 2- user 2-receive antennas MIMO channel where the two users move in the direction indicated in Fig. 4. Figures 7-(a) and -(b) show the 1st user's and the 2nd user's BER performances, respectively, averaged over the 8 second measurement run. Figures 7-(a) and -(b) also show a single user's BER performance curves after the 4th iteration obtained assuming only the desired user exists in the channel. The BER curves show that the MIMO Turbo equalizer can properly separate two moving user's signals in the frequency selective MIMO channels.

VII. Conclusion

We have presented performances of our proposed SC/MMSE S/T MIMO Turbo Equalizer obtained by using field measurement data in an urban area of Tokyo. A serious of simulations were conducted assuming uplink 2-users and 2- receive antennas broadband MIMO channels. BER performances of two static users and two moving users were evaluated. The results verify that our proposed SC/MMSE S/T MIMO Turbo equalizer properly works in real fields. The future work should include analysis of the two impact of channel correlation on performances, and enhancement of accuracy of symbol timing recovery in various MIMO Channel configurations.

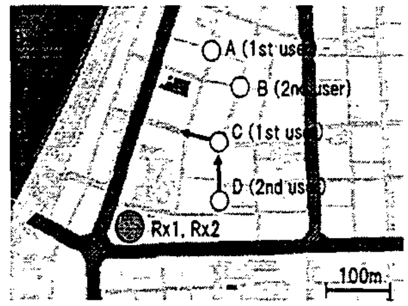

Fig. 4. Field Measurement Area

References

[1] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," Wireless Pers. Commun., vol.6, no.3, pp.311-335, Mar. 1998.

[2] G. J. Foschini, " Layered Space-Time Architecture for Wireless Communicin a Fading Environment When Using Multi-Element Antennas", Bell Labs Technicvol. 1, no. 2, pp. 41-59, Autumn 1996.

[3] T. Abe and T. Matsumoto, "Space-Time Turbo Equalization in Frequency Selective MIMO Channels," VTC 2001 Fall, pp***,

[4] J. Ling, et al., "Multiple transmit multiple receive (MTMR) capacity survey in Manhattan," Electronics Letters 2nd August 2001, vol.37, No. 16.

[5] D. Reynolds and X. Wang "Low Complexity Turbo-Equalization for Diversity Channels," Signal Processing, Elsevier Science Publishers, 81(5) pp.989-995,2001.

[6] G. Bauch and V. Franz "A Comparison of Soft-In/Soft-Out Algorithms for Turbo-Detection " *Proc. International Conference on Telecommunications*, Porto Carras, Greece, pp 259-263, June, 1998

[7] R. S. Thoma, D. Hampicke, A. Richter, G. Sommerkorn, A. Schneider, U.Trautwein, W. Wirnitzer, "Identification of Time-Variant Directional Mobile Radio Channels, "IEEE Trans. On Instrumentation and Measurement, Vol.49, No.2, pp.357-364, April 2000.