A Low-Power Adaptive MIMO Detector for MIMO-OFDM WLAN Systems

Shingo Yoshizawa, Nozomi Miyazaki, Daisuke Nakagawa, and Yoshikazu Miyanaga
Graduate School of Information Science and Technology, Hokkaido University
Kita 14 Nishi 9 Kita-ku, Sapporo, 060-0814 Japan
E-mail: yoshizawa@icn.ist.hokudai.ac.jp

Abstract—A MIMO-OFDM receiver requests high-speed MIMO detection to separate spatially multiplexed signals on real-time processing, which causes large power dissipation due to its high throughput performance. We present an adaptive MIMO detector which adaptively changes the computational speed of MIMO detection by estimating Doppler shifts correlated with fading channel variations. The adaptive detector uses a DVFS technique which dynamically changes a clock frequency and a supply voltage according to the selected computational speed. This work discusses an 8x8 MIMO detector assuming single-user MIMO usage in IEEE802.11ac wireless LAN systems. The conventional and the proposed MIMO detectors have been evaluated in power dissipation.

I. INTRODUCTION

Multiple-input multiple-output orthogonal frequency multiplexing (MIMO-OFDM) is powerful in enhancing communication capacity or reliance and is adopted in current wireless LAN standard of IEEE 802.11n [1]. IEEE 802.11.ac, which is known as next standardization, supports eight spatial streams in single-user MIMO (SU-MIMO) [2]. As MIMO spatial streams increase, the computational and hardware complexities in MIMO-OFDM systems also greatly increase. It is a challenging to design a MIMO-OFDM transceiver with minimal hardware cost and power dissipation in VLSI implementation. Signal detection in a MIMO receiver, called MIMO detection, needs high-speed computation due to its large computational cost. Hardware implementation of MIMO detection is one important issue in current wireless communications. Algorithms for MIMO detection are linear detections [3], [4] ordered successive interference cancellation (OSIC) and non-linear detections [5], [6]. Maximum-likelihood (ML) detection [7], [8] is a non-linear detection. There are trade-offs between MIMO detection performance and computational complexity.

Recent researches have tackled linear detectors in minimum mean squared error (MMSE) for 4x4 MIMO-OFDM systems in terms of a trade-off between computational complexity and detector performance [9], [10]. Our presented MMSE MIMO detectors use pipeline processing on a subcarrier basis and are superior in throughput performance [11], [12]. However, they have not solve an issue in power increase for its high throughput performance. Our research group goes on LSI development of an 8x8 MIMO-OFDM transceiver compatible with the IEEE802.11ac specification. A low-power design is mandatory for further power increase of 8x8 MIMO. This paper describes the implementation of two 8x8 MIMO detectors and proposes an adaptive MIMO detector for power reduction. The proposed detector changes a clock frequency and a supply voltage in the detector according to a Doppler shift correlated with time variations in fading channels. The conventional and the proposed MIMO detectors have been evaluated in power dissipation.

II. DESIGN OF 8X8 MIMO DETECTORS

MIMO-OFDM received signals \( y[k, t] \) with \( M_T \) transmitter and \( M_R \) receiver antennas are described by

\[
y[k, t] = H[k]s[k, t] + n[k, t],
\]

where \( k \) is a subcarrier index, \( t \) is a data symbol index, \( s[k, t] \) is a signal transmitted at \( t \)-th symbol, and \( n \) is a white Gaussian noise vector. \( H[k] \) is a MIMO channel matrix whose elements are given the channel response from \( j \)-th transmitter antenna to \( i \)-th receiver antenna with \( k \)-th subcarrier. The linear MIMO detection is divided into zero-forcing (ZF) and MMSE.
The weight matrix \( G[k] \) in the MMSE criterion is given by
\[
G[k] = (H[k]^H H[k] + \sigma^2 I)^{-1} H[k]^H
\]
where \((\cdot)^H\) denotes the complex conjugate transpose, and \(\sigma^2\) is the noise variance. The decoded signal \( \hat{s}[k, t] \) is given by multiplexing the weight matrix to the received signal.
\[
\hat{s}[k, t] = G[k] y[k, t]
\]

The timing chart in Eqs. (2) to (3) is shown in Fig. 1, which consists of MIMO channel estimation, preprocessing (matrix inversion), and MIMO detection. The channel estimation extracts the MIMO channel matrix of \( H[k] \) from training symbols. The preprocessing calculates the inverted matrix of \( G[k] \). The MIMO detection decodes the original data from the received signals in the data symbols. When a MIMO-OFDM receiver computes the inverted matrix of \( G[k] \) and use it for the MIMO detection in the same packet, the preprocessing should finish by receiving the first data symbol.

The block diagram of a 8x8 MIMO detector is shown in Fig. 2. The input data in the MIMO detection block are given by the estimated MIMO channel matrix of \( H_k \) with \( k \)-th frequency bin and \( M_T \times M_R \) matrix. The matrices of \( P_k, R_k, \) and \( G_k \) are computed as
\[
P_k = H_k^H H_k + \sigma^2 I \quad (4)
\]
\[
Q_k = H_k^H \quad (5)
\]
\[
R_k = P_k^{-1} \quad (6)
\]
\[
G_k = R_k Q_k \quad (7)
\]
The output data of \( G_k \) are stored in the memory unit and retrieved in the MIMO decoding process. We use Strassen’s algorithm for the matrix inversion, which divides a square matrix into four block matrices. For an 8x8 matrix \( \Omega \), it is divided into 4x4 block matrices as
\[
\Omega = \begin{pmatrix} A & B \\ C & D \end{pmatrix},
\]
where \( A, B, C, D \) are the 4x4 matrices. \( \Omega^{-1} \) is calculated by
\[
\Omega^{-1} = \begin{pmatrix} F & -A^{-1} B E^{-1} \\ E^{-1} C A^{-1} & D \end{pmatrix} = \begin{pmatrix} A' & B' \\ C' & D' \end{pmatrix},
\]
\[
F = A^{-1} + A^{-1} B E^{-1} C A^{-1} \quad (10)
\]
\[
E = D - C A^{-1} B \quad (11)
\]
where \( \Omega \) is a Hermitian matrix composing \( C = B^H \) \( B' = C^H \). This property gives the relation of \( A^{-1} B = (CA^{-1})^H \).

The implementation results of 8x8 MIMO detectors on a 90-nm CMOS technology are shown in Table I, where a clock frequency was set to 100 MHz with 1.0-V supply voltage. The complete pipeline provides high-speed processing and increases a LSI scale. The circuit scale of the 9-step pipeline detector is smaller than that of the complete pipeline and has a longer processing delay.
III. ADAPTIVE MIMO DETECTOR

A. Adaptive Detection

The high-speed MIMO detection is mandatory to follow time-varying fading channels in wireless LAN systems. However, if a mobile station does not move and stay on the same location for a long period, a speed of channel variation is quite slow. The graph in Fig. 5 shows time variations in MIMO channels for various Doppler frequency conditions. We use normalized mean square error (NMSE) in this analysis. The simulation parameters in Table I are explained in Section IV.

The NMSE value of $\xi(t)$ is computed as

$$\xi(t) = \frac{\sum_{k=1}^{K} \sum_{m_r=1}^{M_r} \sum_{m_i=1}^{M_i} |\hat{H}_{i,j,k} - H_{i,j,k}(t)|^2}{\sum_{k=1}^{K} \sum_{m_r=1}^{M_r} \sum_{m_i=1}^{M_i} |\hat{H}_{i,j,k}|^2}$$  

where $\hat{H}_{i,j,k}$ is the channel matrix computed in the first packet with $i$-th column, $j$-th row, $k$-th subcarrier. $H_{i,j,k}(t)$ indicates the channel matrix computed in the other packets with a time interval of $t$. The variation of channel matrix depends on the parameters of Doppler frequency. This observation suggests that a receiver does not necessarily update a MIMO channel matrix for every packets for small Doppler frequency, which can extend the computation time in the MIMO detection.

The timing charts of MIMO detection methods are illustrated in Fig. 6. Figure 6(a) shows the conventional MIMO detection which computes and update the channel matrix for every packets. This method follows the time variation of channel matrix than the method A and is superior in robustness with the channel variations.

B. DVFS Power Reduction

A DVFS technique [13] estimates and gives a dynamic operating voltage and frequency. When operating clock frequency is high, the high voltage is required. It causes large power consumption. When operating clock frequency is low, the voltage can be decreased. This case enables power reduction. The model of power consumption in CMOS circuits [14] can be expressed as

$$\text{Power} = C_L V_{DD}^2 f + (A - 1) I_0 e^{-\frac{V_T}{V_{th}}} V_{DD}$$.  

where $C_L$ is a capacitance, $V_{DD}$ is the operating voltage, $f$ is the operating frequency, $A$ is a number of gates, $I_0$ is a leakage current, $V_T$ is a threshold voltage, $V_{th}$ is a thermal voltage, and $\alpha$ is a factor of subthreshold parameters. The first term is a dynamic power which consumes during charging and discharging of additional capacity. The second term is a leakage power which consumes by a leakage current. From Eq. (13), a dynamic power is proportional to the square of the operating voltage, and a leakage power is proportional to
the operating voltage. Power consumption of the whole circuit can be reduced in both a dynamic power and a leakage power by decreasing the operating voltage.

The adaptive MIMO detector with DVFS is shown in Fig. 7. The part under the dotted line operates in dynamic voltage and clock frequency estimated from the FFT outputs in received signals. A phase locked loop (PLL) and a DC/DC converter are used to change voltage and clock frequency dynamically. The DVFS control circuit estimates a Doppler frequency from the FFT outputs and gives the instruction of a clock frequency and voltage for the PLL and the DC/DC converter. Use of DVFS can deal with the change of the number of skipped packets when the Doppler frequency is changed.

### IV. EVALUATION

#### A. Communication Performance

We decided the maximum numbers of skipped packets which do not cause performance degradation even in applying the adaptive MIMO detection. Bit error rate (BER) performance has been measured for the method A and the method B. The simulation parameters are enumerated in Table II. The simulation has been performed in Doppler frequency of 2 to 20 Hz. Figure 8 shows BER performance in the case of 10 Hz. The difference between the best and worst conditions for the numbers of skipped packets is less than 1 dB in 24-dB SNR. It is decided as no performance degradation. Table III shows the simulation results in the maximum numbers of skipped packets for various conditions in Doppler frequency.

#### B. Power Consumption

The adaptive MIMO detection has been implemented into the pipeline 9-step MIMO detector explained in Section III. The evaluation results are shown in Table IV. The clock frequency has been determined by the estimated allowable processing time from the skipped packets in Table III. By lowering a clock frequency, a supply voltage can be decreased. The adaptive MIMO detector indicates maximum 90% of power reduction for the small Doppler frequency conditions.

### V. CONCLUSION

We have presented an adaptive MIMO detector using DVFS to reduce power consumption in an 8x8 MIMO-
OFDM receiver. The adaptive MIMO detection skips packets performing MIMO detection. The DVFS decreases operating clock frequency and supply voltage. We have implemented the proposed detectors and evaluated power consumption. The proposed adaptive MIMO detector has reduced to 1/10 comparing with the conventional MIMO detector.

ACKNOWLEDGMENT

This study is supported in parts by Japan Science and Technology (JST) Agency A-STEP whose project title is “Design and Development of Ultra-Low Power High Speed Wireless Communications LSI”.

REFERENCES


