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Effective SINR Computation for Maximum Likelihood Detector in MIMO Spatial Multiplexing Systems

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Abstract—This paper studies the computation of post-processing signal-to-interference plus noise ratio (SINR) for maximum likelihood detector (MLD) in multiple-input and multiple-output (MIMO)-orthogonal frequency division multiplexing (OFDM) spatial multiplexing systems. We derive an effective post-MLD SINR for each spatial stream, which is computed as post minimum mean-squared error (MMSE) SINR plus gain factor, where the gain factor is adaptively chosen based on the instantaneous channel and modulation format of interfering streams. The post-MLD SINR is then applied to modulation and coding scheme (MCS) selection in adaptive modulation and coding. Simulation results show that the MCS selection using proposed post-MLD SINR can achieve throughput performance close to that of the optimum approach, and considerable gain can be achieved over linear-MMSE receiver.

I. INTRODUCTION

In modern wireless communication systems, adaptive modulation and coding, and multiple-input and multiple-output (MIMO)-orthogonal frequency division multiplexing (OFDM) spatial multiplexing are the key transmission technologies which provides high spectrum efficiency. In addition, maximum likelihood detector (MLD) [1], and its reduced-complexity extensions [2]–[4] are promising receiver technologies for MIMO-OFDM spatial multiplexing systems to fully achieve its potential capacity.

One practical issue on MLD in MIMO spatial multiplexing systems with adaptive modulation and coding is modulation and coding scheme (MCS) selection. In adaptive modulation and coding, the receiver selects most preferable MCS format for given channel condition, and feeds back the MCS index to the transmitter. When the linear minimum mean-squared error (LMMSE) detector is used, MCS selection is straightforward because the post-MMSE processing signal to interference-plus-noise ratio (SINR) can be explicitly computed for each spatial stream using channel estimates, and then MCS for spatial streams are chosen based on the SINR values. However, when MLD is used, MCS selection is not straightforward because the exact post-processing SINR cannot be computed explicitly. One solution would be to select MCS based on the estimates of pair-wise symbol error rate probability [5]. However, in MIMO spatial multiplexing, computing the pair-wise probability would be a computationally expensive since it requires multi-dimensional symbol constellation search.

This paper aims to derive effective post-processing SINR for MLD. We mainly focus on 2-Tx-MIMO OFDM systems that is a baseline configuration for 3GPP LTE standard [6], and the use of non-iterative MLD for low decoding latency. The post-MLD SINR is computed as the post-MMSE SINR plus gain factor, where the gain factor is adaptively chosen based on the instantaneous channel condition and modulation format of interfering streams. We apply the proposed post-MLD SINR to MCS selection for adaptive modulation and coding, and evaluate the throughput performance of 2-by-2 MIMO OFDM systems with various practical factors, such as channel estimation, feedback delay, and channel adaptive precoding.

II. SYSTEM MODEL

Figure 1 shows the system model. This paper focuses on two transmit and $N$ receive antenna ($N \geq 2$) MIMO-OFDM systems with $K$ subcarriers where two independent spatial streams are transmitted simultaneously at each subcarrier. At the transmitter, independent coding and modulation is assumed for each spatial stream, and a common modulation and coding is applied for all subcarriers within a stream [6]. The receiver uses MLD for spatial signal separation followed by stream-wise channel decoders. The received signal vector $r_k \in C^N$ at the $k$-th subcarrier ($k = 1 \ldots K$) is defined as

$$r_k = h_{k1}s_{k1} + h_{k2}s_{k2} + n_k$$

where $h_{kl} \in C^N$ ($l = 1, 2$) is the spatial channel vector of the $l$-th stream. $n_k$ is the AWGN vector of which covariance matrix is defined as $E[n_kn_k^H] = \sigma^2 I_N$. $I_N$ is an $N \times N$ indentity matrix. $s_k$ is the transmitted symbol vector which satisfies $E[s_k s_k^H] = I_2$.

Adaptive modulation and coding is applied, where the receiver performs MCS selection based on the instantaneous channel $h_{kl}$ and $\sigma^2$ to select one MCS providing the highest throughput for each stream. Selected modulation order $M_l$ and coding rate $R_l$ for the $l$-th stream are fed back to the transmitter.
III. MCS SELECTION FOR MIMO-OFDM

A. LMMSE receiver

When the LMMSE receiver is used, the post-MMSE SINR for the \( t \)-th stream at the \( k \)-th subcarrier can be computed as,

\[
\gamma_{mk}^{\text{mmse}} = \frac{h_k^H R_k^{-1} h_{kl}}{1 - h_k^H R_k^{-1} h_{kl}}, \tag{3}
\]

where \( R_k = H_k H_k^T + \sigma^2 I_N \). Once the stream-wise post-MMSE SINR value for each subcarrier is computed, the receiver chooses a single MCS matched to all subcarriers. Several techniques have been studied to select a single MCS from multiple SINR values. This paper employs the average mutual information (MI) scheme [7] that computes an average MI from multiple SINR values, then use it to estimate FER for each MCS with look-up-table, and select one MCS providing the highest throughput.

B. MLD

1) Effective SINR computation: We first assume without loss of generality that the first stream is the desired stream and second stream is the interfering stream. Since MLD performs joint detection by evaluating MIMO channel metric \( -\frac{1}{\sigma^2} |r_k - H_k s_k|^2 \) for multiple hypothesis on \( s_k \), the exact post-processing SINR cannot be derived. Thus, we derive an approximate post-processing SINR. For this aim, the post-MLD SINR of the first stream is first lower-and-upper bounded as

\[
\gamma_{k1}^{\text{mld}} \leq \gamma_{k1}^{\text{mmse}} \leq \gamma_{k1}^{\text{if}}, \tag{4}
\]

where \( \gamma_{k1}^{\text{if}} \equiv \frac{\| h_k \|^2}{\sigma^2} \) is the interference-free SNR of the first stream. An important observation here is as follows. When the second (interfering) stream becomes more detectable by MLD, the post processing SINR of the first stream becomes larger, i.e., \( \gamma_{k1}^{\text{mld}} \rightarrow \gamma_{k1}^{\text{if}} \). This happens, for example, when the modulation order of the second stream is decreased while the channel condition is fixed. On the other hand, when the second stream becomes less detectable, the post processing SINR of the first stream becomes smaller, i.e., \( \gamma_{k1}^{\text{mld}} \rightarrow \gamma_{k1}^{\text{mmse}} \). This occurs, for example, when the modulation order of the second stream is increased. Based on (4), we compute the post-MLD SINR of the first stream as

\[
\gamma_{k1}^{\text{mld}} = \gamma_{k1}^{\text{mmse}} + \alpha_{k1} (\gamma_{k1}^{\text{if}} - \gamma_{k1}^{\text{mmse}}), \tag{5}
\]

where the second term in the right hand side of (5) is the gain factor obtained by MLD compared with the LMMSE detector. According to the observation above, the coefficient \( \alpha_{k1} (0 \leq \alpha_{k1} \leq 1.0) \) is adaptively chosen according to the detectability of the second (interfering) stream. To measure the detectability of the second stream, symbol-error-rate (SER) can be employed. The SER upper-bound of the second stream can be computed by using its post-MMSE SINR value as [8],

\[
P_{k2}^{\text{ser}} = 1 - \left\{ 1 - 2 \left( 1 - \frac{1}{\sqrt{2 M_2}} \right) Q \left( \sqrt{\frac{3 \gamma_{k2}^{\text{mmse}}}{2 M_2}} \right) \right\}^2, \tag{6}
\]

where \( M_2 \) is the modulation order of the second stream, and \( Q(x) = \frac{1}{\sqrt{2 \pi}} \int_{-\infty}^{x} e^{-t^2/2} dt \). Note that in actual implementations, \( Q(x) \) is realized by using a look-up-table.

The observation above also suggests that \( \alpha_{k1} \) is a decreasing function of \( P_{k2}^{\text{ser}} \). In this paper, we define \( \alpha_{k1} \) as,

\[
\alpha_{k1} = \begin{cases} 0 & P_{k2}^{\text{ser}} > 0.3 \\ 0.3 & 0.1 \leq P_{k2}^{\text{ser}} \leq 0.3 \\ 0.7 & 0.05 < P_{k2}^{\text{ser}} \leq 0.1 \end{cases}, \tag{7}
\]

which was optimized by off-line simulations. The optimum \( \alpha_{k1} \) function could be different for different channel models, but in this paper we apply the common \( \alpha_{k1} \) function to all channel models for simple implementation. Finally, (6) and (7) are integrated into a single function,

\[
\alpha_{k1} = f(\gamma_{k2}^{\text{mmse}}, M_2). \tag{8}
\]

In the same way as above, the post-MLD SINR value of the second stream is computed by regarding the first stream as interference,

\[
\gamma_{k2}^{\text{mld}} = \gamma_{k2}^{\text{mmse}} + \alpha_{k2} (\gamma_{k2}^{\text{if}} - \gamma_{k2}^{\text{mmse}}) \tag{9}
\]

with

\[
\alpha_{k2} = f(\gamma_{k1}^{\text{mmse}}, M_1). \tag{10}
\]

One further extension of the SINR computation above is to introduce iteration. We can iteratively re-compute the \( \alpha_{k1} \) and \( \alpha_{k2} \) based on the effective SINR value \( \gamma_{k1}^{\text{mld}} \) and \( \gamma_{k2}^{\text{mld}} \) to improve the accuracy of the SINR value. In this paper, however, the iterative refinement is not used in the our performance.
evaluation below for computationally efficient implementation.

2) MCS selection: Figure 2 shows the block diagram to compute the effective SINR computation. As shown in the figure, computing the post-MLD SINR value of each stream requires the modulation order of the interfering stream. Thus, we perform MCS selection in the following procedure: (1) determine a set of candidate modulation pairs, (2) for each modulation pair, compute the post-MLD SINR for each stream and select a coding rate based on the SINR value, (3) choose one modulation pair and coding rates that maximizes the estimated throughput. We use the average MI scheme [7] to choose coding rates based on the post-MLD SINR values.

Regarding the choice of candidate modulation pairs in the step (1), straight forward way would be to consider all possible modulation pairs. For example, if QPSK, 16QAM and 64QAM are used, there will be nine pairs. However, to remove unnecessary pair, we generate only three pairs as follows. We first choose coding rates based on the post-MLD SINR values and select a coding rate based on the SINR value, (3) choose one modulation pair and coding rates that maximizes the estimated throughput. We use the average MI scheme [7] to choose coding rates based on the post-MLD SINR values.

where $\Delta_{kri}$ is the potential SINR gain if the $i$-th stream was not present on the channel. Thus,

$$\gamma_{kr}^{\text{mld}} = \gamma_{kr}^{\text{mmse}} + \sum_{i=1, i \neq r}^{i=R} \alpha_{kri} \Delta_{kri}$$

holds. The coefficients $\alpha_{kri}$ are function of the post-MMSE SINR value and modulation format of $i$-th stream, which could be optimized by offline simulations.

IV. SIMULATION RESULTS

Simulations were conducted assuming 2-by-2 MIMO-OFDM spatial multiplexing systems, 1.0-msec transmission frame length with 14 OFDM symbols, 1.8 MHz bandwidth with 120 subcarriers and 15 kHz subcarrier spacing. For adaptive modulation and coding, the following 15 level MCS were used: QPSK with coding rate $R=1/16$, $1/8$, $1/6$, $1/3$, $4/9$, $3/5$, 16QAM with $R=2/5$, $1/2$, $3/5$, 64QAM with $R=4/9$, $5/9$, $2/3$, $3/4$, $6/7$, $12/13$. The turbo code with memory three and mother code rate $1/3$ was used. Maximum Doppler frequency was 5.55 Hz. As a performance reference, we evaluated the throughput performance of MLD with optimum MCS selection, where the receiver simulates FER (without using a look-up-table) for all possible MCS combinations of the two streams for each channel realization to find the MCS combination which would provide the highest throughput. This exhaustive approach would yield optimum performance when MCS feedback delay is negligible. In addition, the throughput performance of LMMSE was evaluated. We first evaluate throughput performances with a small MCS feedback delay of 1.0 msec. Figures 3 (a) and 3 (b) show the throughput performance in uncorrelated MIMO channels with 1-path, and the 6-path typical urban (TU) [9] multi-path delay profiles, respectively. Figures 4 (a) and 4 (b) show the throughput performance in correlated MIMO channels with TU and SCM-C [10] channel models, respectively, where correlation factor 0.5 was assumed between adjacent transmit antennas for the TU channel model. The figures show that MLD with MCS selection using the proposed effective SINR can achieve about 2.0 dB gain over the LMMSE receiver in mid-to-high SNR regions. The performance loss of the proposed scheme compared with the optimum scheme is due to use of the SER lower-bound by using the post-MMSE SINR value (6), which could underestimate MCS.

We next evaluate the performance with a practical MCS feedback delay of 4.0 msec. Figures 5 shows the throughput performance in the correlated MIMO channels with the TU delay profile. The figure shows that in the presence of 4.0 msec channel ambiguity, the throughput performance of the proposed approach becomes closer to that of the optimum approach. This is because the proposed approach is more robust to the channel variation due to the MCS underestimation effect.

The results above also show that the throughput gain of MLD compared with LMMSE becomes smaller in lower SNR regions. To examine this, Figure 6 shows FER performance.
after decoding for various MCS without link adaptation, where the same MCS was assumed for both streams. Inter-stream symbol interleaving was applied to eliminate the performance loss due to use of common MCS format for both streams. The figure shows that when lower coding rates are used, the FER performance gain by MLD over LMMSE becomes smaller. This is because in lower coding rates, decoding is the dominant part that determines the overall FER performance especially when a strong code such as the turbo code is used. Therefore, in lower-SNR regions, the throughput performance gain of MLD over LMMSE detector becomes smaller because MCS with relatively lower coding rates are selected by MCS. Note, if iterative detection and decoding is introduced, the performance gain of MLD over LMMSE detector will be increased due to decoding gain.

Finally, we evaluate the throughput performances with more practical settings with pilot-assisted channel estimation, codebook based precoding, and rank adaptation. In addition to the MCS formats, the receiver also feeds back preferable number of spatial streams, and precoding matrix index. The same pilot grid and precoder codebook as in LTE standard [6]. The pilot assisted channel estimation with Wiener interpolation was
channel estimation, channel adaptive rank and precoder performance gain is also demonstrated with pilot assisted the throughput performance of the LMMSE receiver. Similar with the optimum approach, and about 2.0 dB better than MLD with the proposed link adaptation is close to that active modulation and coding. The throughput performance of post-MLD SINR is then applied in MCS selection for adap-
scheme for MIMO-OFDM spatial multiplexing systems. The
more frequently in lower SNR regions due to rank adaptation.
becomes smaller because single-stream transmission occurs regions, performance difference between MLD and LMMSE over LMMSE detector in high SNR regions. In low SNR MLD with proposed MCS selection achieves considerable gain with this practical condition,
correlation factor 0.5, 4.0 msec feedback delay, ideal channel estimation

Fig. 5. Throughput performance: 2-by-2 MIMO, TU channel with Tx correlation factor 0.5, 4.0 msec feedback delay, ideal channel estimation

Fig. 6. FER performance: 2-by-2 MIMO, uncorrelated, 6-path TU channel, ideal channel estimation

Fig. 7. Throughput performance: 2-by-2 MIMO, TU channel with Tx correlation factor 0.5, 4.0 msec feedback delay, real channel estimation, rank adaptation, channel adaptive precoding

V. CONCLUSION
This paper proposed effective post-MLD SINR computation scheme for MIMO-OFDM spatial multiplexing systems. The post-MLD SINR is then applied in MCS selection for adaptive modulation and coding. The throughput performance of MLD with the proposed link adaptation is close to that with the optimum approach, and about 2.0 dB better than the throughput performance of the LMMSE receiver. Similar performance gain is also demonstrated with pilot assisted channel estimation, channel adaptive rank and precoder adaptation.

REFERENCES