HARQ Throughput Performance of Training Sequence Aided SC-MIMO Using Reduced Complexity ML Block Detection

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Abstract—**For high-speed packet access, hybrid automatic repeat request (HARQ) and multi-input multi-output (MIMO) multiplexing are indispensable techniques. Single-carrier (SC) MIMO block transmission using frequency-domain signal detection such as the frequency-domain linear detection based on the minimum mean square error criterion (MMSED) can improve the HARQ throughput performance over the frequency-selective fading channel. However, the performance improvement is limited due to not only an inter-antenna interference (IAI) but also an inter-symbol interference (ISI) resulting from a severe frequency-selective fading. In this paper, we propose to jointly use a training sequence (TS) aided SC block transmission and a near maximum likelihood (ML) block detection using QR decomposition and M-algorithm (QRM-MLBD) for SC-MIMO HARQ. It is shown, by computer simulation, that SC-MIMO using TS aided QRM-MLBD significantly improves the HARQ throughput performance compared to an often used cyclic prefix (CP) inserted SC-MIMO while significantly reducing the computational complexity. It is also shown that proposed TS aided QRM-MLBD achieves a significantly higher throughput than the MMSED particularly when higher level modulation is used.**

Keywords-component; Single-carrier, MIMO, HARQ, near ML detection, QR decomposition, M-algorithm, training sequence

I. INTRODUCTION

Packet access will be the core technology of the next generation mobile communication systems. Very high-speed and high-quality packet transmissions in a limited bandwidth can be achieved by the joint use of multi-input multi-output (MIMO) multiplexing [1] and hybrid automatic repeat request (HARQ) [2]. The use of high level modulation is essential. However, the data transmission using high level modulation is vulnerable not only to the inter-antenna interference (IAI) but also to the channel distortion. The channel distortion is caused due to the presence of many propagation paths having different time delays. MIMO spatial multiplexing with orthogonal frequency-division multiplexing (OFDM) [3] has been adopted in several wireless communication standards because of its robustness against frequency-selective fading. However, OFDM has higher peak-to-average power ratio (PAPR) than the single-carrier (SC) transmission. Recently, SC-MIMO spatial multiplexing has been gaining an increasing popularity because of its lower PAPR property [4-5]. The use of cyclic prefix (CP) and frequency-domain signal detection such as the frequency-domain linear detection based on the minimum mean square error criterion (MMSED) can improve the HARQ throughput performance of SC-MIMO with a low complexity. However, the performance improvement is limited and a big performance gap still exists from the maximum likelihood (ML) performance due to the presence of residual inter-symbol interference (ISI) and IAI when higher level modulation (e.g., 16QAM, 64QAM) is used.

The computational complexity of ML detection [6] is extremely high. Recently, near ML-based reduced complexity signal detection was proposed [7] for CP inserted SC (CP-SC) MIMO spatial multiplexing (we call this detection scheme as the ML block detection using QR decomposition and M-algorithm (QRM-MLBD)). In QRM-MLBD, QR decomposition is applied to a concatenation of the space and frequency-domain channel and discrete Fourier transform (DFT). QRM-MLBD can significantly improve the packet error rate (PER) performance of CP-SC MIMO spatial multiplexing when compared to the MMSE detection [7]. However, the use of a fairly large number M of surviving paths in the M-algorithm is required, leading to high computational complexity. This is because if smaller M is used, the probability of removing the correct path at early stages increases. Recently, in order to further reduce the required number M, we proposed a training sequence (TS) aided QRM-MLBD for SC-MIMO spatial multiplexing [8]. In TS aided QRM-MLBD, TS aided SC (TS-SC) block transmission [9] is used instead of an often used CP-SC block transmission and its TS is utilized to reduce the probability of removing the correct path at early stages. TS aided QRM-MLBD achieves the PER performance similar to the conventional QRM-MLBD while significantly reducing the computational complexity.

A combination of SC-MIMO with rate compatible punctured turbo (RCPT) coded HARQ [10] is one of promising packet transmission techniques. In RCPT coded HARQ, an information packet is first transmitted with parity bits for error detection or none error correction. If the retransmission request is received, incremental redundancy bits are transmitted. Since the first packet transmission is uncoded (or coded with higher rate), the throughput performance of the SC-MIMO HARQ using MMSED cannot be much improved. The use of QRM-MLBD is expected to be more effective. However, the previous work [7, 8], HARQ has not been considered. In this paper, to improve the HARQ throughput of SC-MIMO, we propose to jointly use the TS aided SC block transmission and the QRM-MLBD for SC-MIMO HARQ. It is shown, by computer simulation, that SC-MIMO using TS aided QRM-MLBD significantly improves the HARQ throughput performance compared to an often used CP inserted SC-MIMO while significantly

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reducing the computational complexity. It is also shown that proposed TS aided QRM-MLBD achieves a significantly higher throughput than the MMSED particularly when higher level modulation is used.

The remainder of this paper is organized as follows. Sect. II introduces the transmission system model of turbo-coded SC-MIMO HARQ using TS aided QRM-MLBD. In Sect. III, we show the computer simulation results of the throughput performance. Sect. IV offers some concluding remarks.

II. SC-MIMO HARQ USING TS AIDED QRM-MLBD

A. HARQ

In this paper, we consider the HARQ type II S-P4 [11] and turbo coding with rate R=1/3, as illustrated in Fig. 1. The turbo encoder outputs the systematic bit sequence and two parity bit sequences. These sequences are punctured into five sequences (including systematic bit sequence) by the puncturing matrices given by

$$\begin{bmatrix}1&1&1&1\\0&0&0&0\\0&0&0&0\end{bmatrix}\begin{bmatrix}0&0&0&0\\1&0&0&0\\0&0&1&0\end{bmatrix}\begin{bmatrix}0&0&0&0\\0&1&0&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}0&0&0&0\\0&0&1&0\\1&0&0&0\end{bmatrix}\begin{bmatrix}0&0&0&0\\0&0&0&1\\0&1&0&0\end{bmatrix}, \tag{1}$$

where the 1st, 2nd, and 3rd rows denote the puncturing pattern for the systematic bit sequence, 1st parity bit sequence, and 2nd parity bit sequence, respectively.

For the first transmission, only the systematic bit sequence is transmitted. At the receiver, data decision and error detection are performed. If any error is detected in the received packet, second transmission is requested from the receiver by sending an NACK signal. When the NACK signal is received at the transmitter, the second packet (consisting of the punctured parity bit sequence) is transmitted. At the receiver, turbo decoding is carried out by using the first and second received packets. If any error is detected after turbo decoding, the NACK signal is transmitted again. One of the punctured parity bit sequences is transmitted each time the NACK signal is received at the transmitter until the 5th packet transmission. After the 5th packet transmission, the same packet is retransmitted.

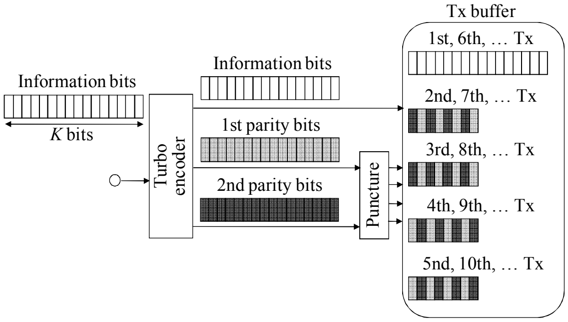


Figure 1. HARQ type II S-P4.

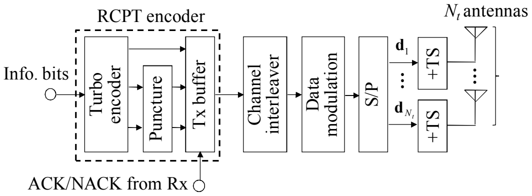
B. Signal Transmission Model

System model of SC-MIMO HARQ using TS aided QRM-MLBD is illustrated in Fig. 2. Throughout the paper, the symbol-spaced discrete time representation is used. At the transmitter, after turbo coding and puncturing, the coded bit sequence is stored in the transmitter buffer. The coded bit sequence is transformed into a data-modulated symbol sequence. Then, the data-modulated symbol sequence is serial-to-parallel (S/P) converted to N_t parallel symbol sequence, each to be transmitted from a different transmit antenna and each parallel symbol sequence is divided into a sequence of symbol blocks of N_c symbols each. The data symbol block of n_t-th transmit antenna can be expressed using the vector form as $\mathbf{d}_{n_t}=[d_{n_t}(0),...,d_{n_t}(t),...,d_{n_t}(N_c-1)]^T$, where $(.)^T$ expresses the transposition. Before the transmission, the TS of length N_g symbols is appended at the end of each block. The block $\mathbf{s}_{n_t}=[s_{n_t}(0),...,s_{n_t}(t),...,s_{n_t}(N_c+N_g-1)]^T$ to be transmitted is expressed using the vector form as

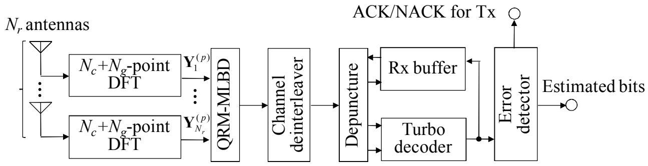
$$\mathbf{s}_{n_t}=\begin{bmatrix}\mathbf{d}_{n_t}\\ \mathbf{u}_{n_t}\end{bmatrix}, \tag{2}$$

where $\mathbf{u}_{n_t}=[u_{n_t}(0),...,u_{n_t}(t),...,u_{n_t}(N_g-1)]^T$ denotes the TS vector which is identical for all blocks. The TS-SC block structure is illustrated and compared to CP-SC transmission in Fig. 3. The difference from CP-SC transmission is that CP is replaced by TS. In order to let TS to play the role of CP, DFT size at the receiver must be the sum of number of useful data symbols and the TS length. In this paper, to keep the same data rate as CP-SC, the data symbol block length and the TS length need to be set to N_c and N_g, respectively. Therefore, the DFT size to be used at the receiver is N_c+N_g symbols for TS-SC while it is N_c symbols for CP-SC.

The signal block is transmitted over a frequency-selective fading channel. The received signal is transformed by N_c+N_g-point DFT into the frequency-domain signal. Then, QRM-MLBD is carried out.

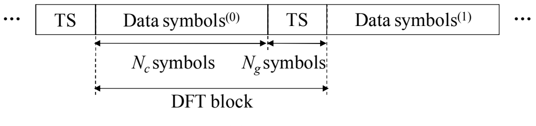


(a) Transmitter

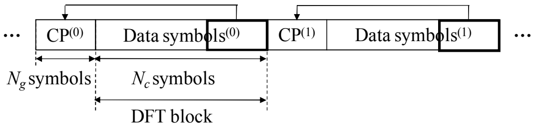


(b) Receiver

Figure 2. System model of SC- MIMO HARQ using TS aided QRM-MLBD.



(a) TS-SC



(b) CP-SC

Figure 3. Block structure.

C. QRM-MLBD

Consider that the pth retransmitted packet has been received. The frequency-domain received signal vector at the n_r-

th receive antenna $\mathbf{Y}_{n_r}^{(p)}=[Y_{n_r}^{(p)}(0),...,Y_{n_r}^{(p)}(k),...,Y_{n_r}^{(p)}(N_c+N_g-1)]^T$ after N_c+N_g-point DFT is expressed as

$$\mathbf{Y}_{n_r}^{(p)}=\sqrt{\frac{2E_s}{T_s}}\sum_{n_t=1}^{N_t}\mathbf{H}_{n_r,n_t}^{(p)}\mathbf{F}\mathbf{s}_{n_t}+\mathbf{N}_{n_r}^{(p)}\,, \tag{3}$$

where E_s and T_s are respectively the symbol energy and duration, $\mathbf{F}$ is the DFT matrix of size (N_c+N_g)×(N_c+N_g), $\mathbf{H}_{n_r,n_t}^{(p)}$ is the frequency-domain channel matrix between the n_t-th transmit antenna and n_r-th receive antenna in the p-th retransmission, and $\mathbf{N}_{n_r}^{(p)}=[N_{n_r}^{(p)}(0),...,N_{n_r}^{(p)}(k),...,N_{n_r}^{(p)}(N_c+N_g-1)]^T$ is the frequency-domain noise vector.

From Eq. (3), the $N_r(N_c+N_g)\times 1$ overall frequency-domain received signal $\mathbf{Y}^{(p)}=[\{\mathbf{Y}_1^{(p)}\}^T,...,\{\mathbf{Y}_{N_r}^{(p)}\}^T]^T$ is given by

$$\begin{aligned}\mathbf{Y}^{(p)}&=\sqrt{\frac{2E_s}{T_s}}\begin{bmatrix}\mathbf{H}_{1,1}^{(p)}\mathbf{F} & \mathbf{H}_{1,2}^{(p)}\mathbf{F} & \cdots & \mathbf{H}_{1,N_t}^{(p)}\mathbf{F}\\ \mathbf{H}_{2,1}^{(p)}\mathbf{F} & \mathbf{H}_{2,2}^{(p)}\mathbf{F} & \cdots & \mathbf{H}_{2,N_t}^{(p)}\mathbf{F}\\ \vdots & \vdots & \ddots & \vdots\\ \mathbf{H}_{N_r,1}^{(p)}\mathbf{F} & \mathbf{H}_{N_r,2}^{(p)}\mathbf{F} & \cdots & \mathbf{H}_{N_r,N_t}^{(p)}\mathbf{F}\end{bmatrix}\begin{bmatrix}\mathbf{s}_1\\ \vdots\\ \mathbf{s}_{N_t}\end{bmatrix}+\begin{bmatrix}\mathbf{N}_1^{(p)}\\ \vdots\\ \mathbf{N}_{N_r}^{(p)}\end{bmatrix},\\ &=\sqrt{\frac{2E_s}{T_s}}\mathbf{H}^{(p)}\mathbf{s}+\mathbf{N}^{(p)}\end{aligned} \tag{4}$$

where $\mathbf{H}^{(p)}$ is an equivalent channel matrix of size $N_r(N_c+N_g)\times N_t(N_c+N_g)$, which is a concatenation of the space and frequency-domain channel and DFT, $\mathbf{s}$ is the $N_t(N_c+N_g)\times 1$ overall transmit symbol vector, and $\mathbf{N}^{(p)}$ is the $N_r(N_c+N_g)\times 1$ overall noise vector.

Until the 5th packet is received ($0\leq p<5$), the following TS aided QRM-MLBD [8] is carried out. QRM-MLBD consists of three steps; ordering, QR decomposition, and M-algorithm. The ordered overall transmit symbol vector $\mathbf{s}^{order}$ can be expressed as

$$\begin{aligned}\mathbf{s}^{order}&=[s_1(0),...,s_{N_t}(0),...,s_1(N_c+N_g-1),...,s_{N_t}(N_c+N_g-1)]^T\\ &=[\mathbf{d}^T(0),\mathbf{d}^T(1),...,\mathbf{d}^T(N_c-1),\mathbf{u}^T(0),...,\mathbf{u}^T(N_g-1)]^T\end{aligned}, \tag{5}$$

where $\mathbf{d}^T(t)$ and $\mathbf{u}^T(t)$ denote the data symbol vector and TS vector at t-th symbol of size $N_t\times 1$, respectively. After ordering, the QR decomposition is applied to the ordered equivalent channel matrix $\mathbf{H}^{(p)}$ to obtain $\mathbf{H}^{(p)}=\mathbf{Q}^{(p)}\mathbf{R}^{(p)}$, where $\mathbf{Q}^{(p)}$ is an $N_r(N_c+N_g)\times N_t(N_c+N_g)$ unitary matrix and $\mathbf{R}^{(p)}$ is an $N_t(N_c+N_g)\times N_t(N_c+N_g)$ upper triangular matrix. The transformed frequency-domain received signal $\hat{\mathbf{Y}}^{(p)}=[\hat{Y}^{(p)}(0),...,\hat{Y}^{(p)}(N_t(N_c+N_g)-1)]^T$ is obtained as

$$\begin{aligned}\hat{\mathbf{Y}}^{(p)}&=\{\mathbf{Q}^{(p)}\}^H\mathbf{Y}^{(p)}\\ &=\sqrt{\frac{2E_s}{T_s}}\mathbf{R}^{(p)}\mathbf{s}^{order}+\{\mathbf{Q}^{(p)}\}^H\mathbf{N}^{(p)}\end{aligned}. \tag{6}$$

From Eq. (6), the ML solution can be obtained by searching for the best path having the minimum Euclidean distance in the tree diagram composed of $N_t(N_c+N_g)$ stages. M-algorithm [12] can be applied to reduce the computational complexity. In each stage, the best M paths are selected as surviving paths by comparing the path metrics based on the squared Euclidean distance for all surviving paths and are passed to the next stage. In the case of first transmission (p=0), the data demodulation is carried out by tracing back the path having the smallest path metric at the last stage. On the other hand, when $p\geq 1$, the log likelihood ratio (LLR) is used as the soft-input in the decoder. When QRM-MLBD is used, however, the LLR values cannot be directly computed since surviving paths at the last stage do not necessarily contain both 1 and 0 for every coded bit. In this paper, we apply the LLR calculation method proposed in [13]. The approximate LLR values are computed at every stage by using path metric and are updated successively as tree search progresses. If the LLR value cannot be computed at the last stage, the recently updated approximate LLR value at the upper stage is used.

It can be understood from Eqs. (5) and (6) that in TS-SC MIMO multiplexing with ordering, TSs are localized at the bottom of the overall transmit signal vector of size $N_t(N_c+N_g)\times 1$. This helps to improve the detection performance of the MLD using M-algorithm. In the case of SC-MIMO block transmissions, the magnitude of a complex-valued element closer to the lower right positions of matrix $\mathbf{R}$ may drop with higher probability. The received signal powers associated with symbols to be detected at early stages in the M-algorithm significantly drop and hence, the probability of removing the correct path at early stages may increase when a smaller M is used. However, in TS-SC MIMO, the symbols to be detected at early stages in the M-algorithm are symbols belonging to the known TSs. Therefore, the probability of removing the correct path can be significantly reduced even if small M is used.

D. Packet Combining

For the HARQ type II S-P4 [11] assumed in this paper, until the 5th packet is received, turbo decoding with incremental redundancy [14] is performed after QRM-MLBD. As the number of retransmissions increases, the resultant code rate decreases. After the 5th packet transmission ($p\geq 5$), the same packet is retransmitted. If further transmissions are needed, joint QRM-MLBD combined with packet combining (called recursive QRM-MLBD) [15] is utilized to obtain the time diversity gain is obtained since the same packet is retransmitted. Recursive QRM-MLBD is formed as

$$\begin{bmatrix}\tilde{\mathbf{R}}^{(p-5)}\\ \mathbf{H}^{(p)}\end{bmatrix}=\tilde{\mathbf{Q}}^{(p)}\tilde{\mathbf{R}}^{(p)} \tag{7}$$

and

$$\hat{\mathbf{Y}}^{(p)}=\{\tilde{\mathbf{Q}}^{(p)}\}^H\begin{bmatrix}\hat{\mathbf{Y}}^{(p-5)}\\ \mathbf{Y}^{(p)}\end{bmatrix}, \tag{8}$$

where $\tilde{\mathbf{Q}}^{(p)}$ is an $(N_t(N_c+N_g)+N_r(N_c+N_g))\times N_t(N_c+N_g)$ unitary matrix and $\tilde{\mathbf{R}}^{(p)}$ is an $N_t(N_c+N_g)\times N_t(N_c+N_g)$ upper triangular matrix.

III. COMPUTER SIMULATION

The throughput performance of SC-MIMO HARQ using TS aided QRM-MLBD is evaluated by computer simulation. The simulation condition is summarized in Table I. We assume N_c=64, N_g=16, and L=16-path frequency-selective block Rayleigh fading channel with uniform power delay profile. Independent channel is assumed for each retransmission. The perfect synchronization, channel estimation, and error detection are assumed. Furthermore, no transmission error in

ACK/NACK is assumed. We employ a rate 1/3 turbo encoder using two (13, 15) recursive systematic convolutional (RSC) component encoders. Log-MAP decoding with 8 iterations is assumed. The packet size is set to K=3072.

TABLE I. COMPUTER SIMULATION CONDITION

Channel coding	R=1/3 (13, 15) RSC encoder Log-MAP decoding with 8 iterations	
HARQ	HARQ type II S-P4	
Transmitter	Data modulation	QPSK, 16QAM, 64QAM
	Number of transmit antennas	N_t=2, 4
	Data symbol block length	N_c=64
	TS or CP lengths	N_g=16
Channel	Fading type	Frequency-selective block Rayleigh
	Power delay profile	L=16 path uniform power delay profile
Receiver	Number of receive antennas	N_r=2, 4
	Channel estimation	Ideal

A. *Throughput Performance*

The throughput performance of SC-MIMO HARQ using TS aided QRM-MLBD is plotted in Fig. 4 as a function of average received symbol energy-to-noise power spectrum density ratio E_s/N_0 for M=1, 4, 16, 64, and 256. For comparison, the throughput performance of SC-MIMO HARQ using the conventional QRM-MLBD is also plotted. The modulation level which gives the best throughput is selected for each E_s/N_0. It can be seen from Fig. 4 that TS aided QRM-MLBD provides better throughput performance than the conventional QRM-MLBD when the same M is used. This is because the use of TS instead of CP significantly reduces the probability of removing the correct path at early stages in the M-algorithm even if small M is used. In going from N_t=N_r=2 to N_t=N_r=4, the performance improvement by the TS aided QRM-MLBD gets larger. When N_t=N_r=2 and M=16, the E_s/N_0 reduction is about 1.6dB, 2.2dB, and 2.8dB for the throughput=2.5bps/Hz, 5.0bps/Hz, and 7.5bps/Hz, respectively. When N_t=N_r=4 and M=16, the E_s/N_0 reduction is about 3.6dB, 4.6dB, and 5.5dB for the throughput=5.0bps/Hz, 10bps/Hz, and 15bps/Hz, respectively.

Figure 5 compares the throughput performances of TS-SC MIMO HARQ using TS aided QRM-MLBD and MMSED. With MMSED, when the same packet is retransmitted, MMSE packet combing [16] is used as the packet combing scheme. It can be seen from Fig. 5 that the throughput performance is significantly improved in a high E_s/N_0 region by using TS aided QRM-MLBD. When N_t=N_r=2 and M=16, the E_s/N_0 reduction from MMSED is about 3.3dB and 9.5dB for the throughput=5.0bps/Hz and 7.5bps/Hz, respectively. When N_t=N_r=4 and M=16, the E_s/N_0 reduction from MMSED is about 5.0dB and 13.2dB for the throughput=10bps/Hz and 15bps/Hz, respectively. It can be seen from the results that the use of TS-aided QRM-MLBD is more effective when high level data modulation is used and during the first transmission.

B. *Computational Complexity*

The computational complexity of TS aided QRM-MLBD is discussed. The complexity here is defined as the number of complex multiplications. The required number of multiplications is shown in Table II. In Table II, X denotes the modulation level. First, we discuss the complexity comparison between TS aided QRM-MLBD and the conventional QRM-MLBD. TS aided QRM-MLBD achieves better throughput performance even if small M is used. Hence, TS aided QRM-MLBD reduces significantly the computational complexity required for the squared Euclidean distance calculations. It can be seen from Fig. 4 that TS aided QRM-MLBD with M=4 achieves better throughput performance than the conventional QRM-MLBD with M=256 in all E_s/N_0 region for both N_t=N_r=2 and N_t=N_r=4. When N_t=N_r=2(4), the overall computational complexity of TS aided QRM-MLBD with M=4 is about 40(66) %, 13(23) %, and 4.5(7.4) % of that of the conventional QRM-MLBD with M=256 for QPSK, 16QAM, and 64QAM, respectively (N_c=64 and N_g=16).

Next, we discuss the complexity comparison between TS aided QRM-MLBD and MMSED. TS aided QRM-MLBD provides significantly higher throughput performance at the cost of increased complexity. When N_t=N_r=2(4), TS aided QRM-MLBD with M=4 requires about 20(58), and 39(102) times higher computational complexity than MMSED at E_s/N_0=17 and 27dB, respectively (N_c=64 and N_g=16).

TABLE II. NUMBER OF MULTIPLICATIONS

TS aided QRM-MLBD	DFT	$N_r(N_c+N_g)^2$
	QR decomposition	$N_rN_t^2(N_c+N_g)^3+N_rN_t(N_c+N_g)^2$
	Multiplication of $\mathbf{Q}^H$	$N_rN_t(N_c+N_g)^2$
	Squared Euclidian distance calculations	$X\{2+(M/2)(N_tN_c+4)(N_tN_c-1)\}$ $+N_t^2N_g(N_c+N_g)$
Conventional QRM-MLBD	DFT	$N_rN_c\log_2N_c$
	QR decomposition	$N_rN_t^2N_c^3+N_rN_tN_c^2$
	Multiplication of $\mathbf{Q}^H$	$N_rN_tN_c^2$
	Squared Euclidian distance calculations	$X\{2+(M/2)(N_tN_c+4)(N_tN_c-1)\}$
MMSED	DFT/IDFT	$(N_r+N_t)(N_c+N_g)^2$
	Weight generation	$(N_r^3+2N_r^2N_t)(N_c+N_g)$
	Weight multiplication	$N_tN_r(N_c+N_g)$
	LLR calculation	$N_t\{N_t(N_r+1)+N_r+2\}(N_c+N_g)$ $+2XN_tN_c$

IV. CONCLUSION

To realize the high-speed packet access, the use of MIMO multiplexing and high level modulation is essential. However, with MMSED, the throughput performance of SC-MIMO HARQ significantly degrades due to the ISI and IAI. In this paper, to improve the throughput of SC-MIMO HARQ, we proposed to use a combination of TS-SC and QRM-MLBD. We evaluated, by computer simulation, the HARQ throughput performance of TS-SC MIMO using QRM-MLBD. We showed that the TS-aided SC-MIMO using QRM-MLBD significantly improves the throughput performance compared to the conventional CP inserted SC-MIMO while significantly reducing the computational complexity. We also showed that TS aided QRM-MLD provides significantly higher throughput performance than MMSED especially when high level data modulation is used. Hence, the TS-aided QRM-MLBD is promising for high-speed packet access.

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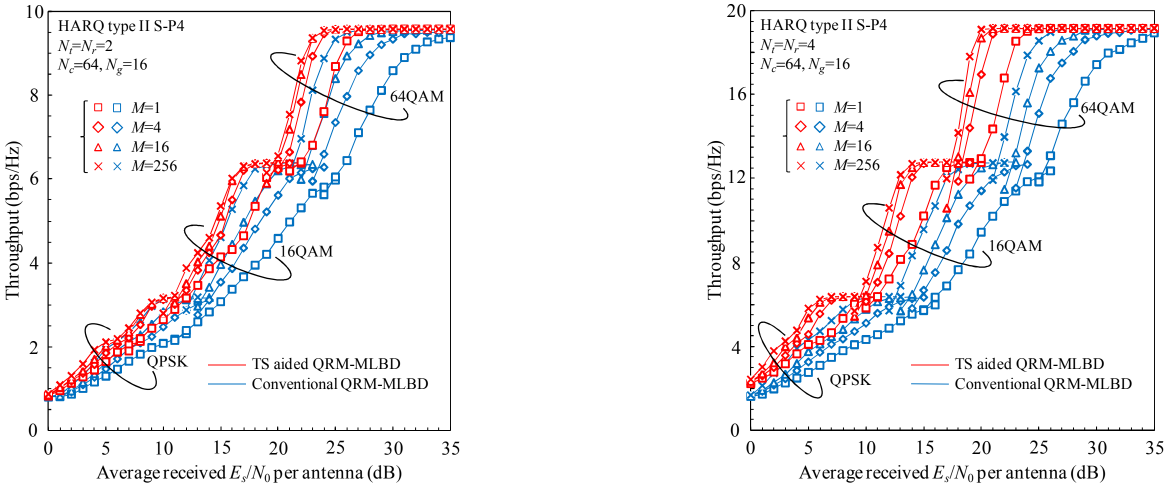
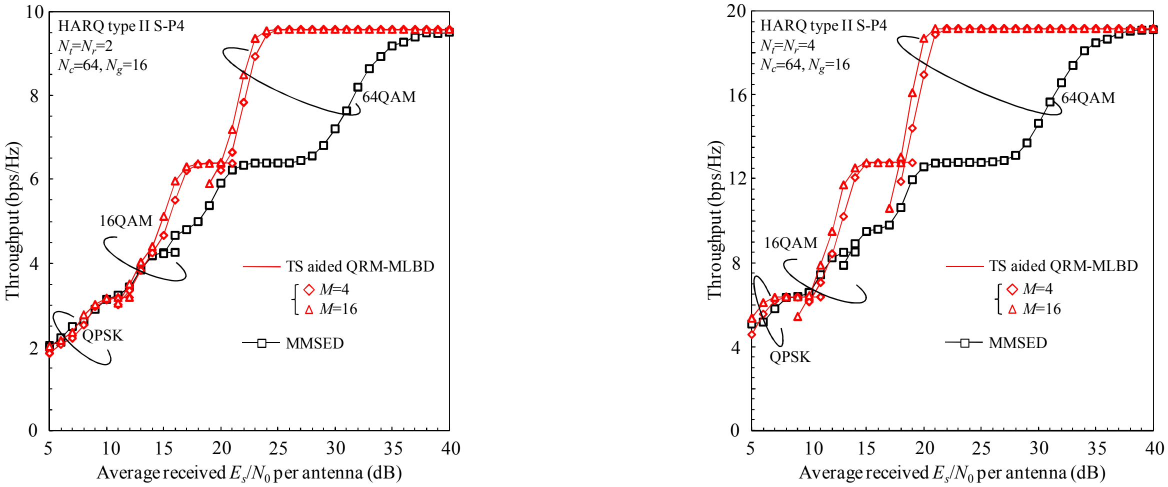


(a) $N_t=N_r=2$

(b) $N_t=N_r=4$

Figure 4. Throughput performance of SC-MIMO HARQ using TS aided QRM-MLBD and the conventional QRM-MLBD.



(a) $N_t=N_r=2$

(b) $N_t=N_r=4$

Figure 5. Throughput performance comparison between TS aided QRM-MLBD and MMSED.