UEP for Wireless Video Streaming Using Spatially Multiplexed MIMO System With a Suboptimal Joint Detection

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***Abstract*—Recently, unequal error protection (UEP) techniques for video transmission over multiple-input multiple-output (MIMO) wireless channel have been actively researched. Spatially multiplexed (SM) MIMO system with joint detection achieves a good bit error rate (BER) performance as well as a high data rate, however, UEP can not be implemented because all the physical (PHY) layer signals are jointly detected. In transmitting video streams, peak signal to noise ratio (PSNR) is important rather than BER, and it is well known that PSNR is improved by UEP. In this paper, we propose an UEP technique for wireless video streaming using SM MIMO system with a suboptimal joint signal detection method. Computer simulations demonstrate that the PSNR performance of QR-LRL-based UEP, that is computationally very efficient when compared with the conventional optimal maximum likelihood (ML) detection, is slightly better than that of the optimal ML detection that is considerably more computation intensive.**

***Keywords*-UEP, H.264/AVC, MIMO, Joint Detection, ML, Spatial Mutiplexing.**

I. INTRODUCTION

Video streaming service in wireless environments is a challenging task that requires both high data transmission speed and high transmission reliability [1]. Wireless channel is characterized by limited spectral bandwidth, limited transmit power, and unstable channel gains [2]. Consequently, error-resilient video streaming at a high speed using these limited resources is a demanding task in wireless video communications.

A popular application (APP) layer H.264/AVC was designed to enable network-friendly video streaming as well as enhanced compression efficiency [1]. Various error resiliency schemes can be used for H.264/AVC video streaming such as semantics, syntax error detection, data partitioning (DP), slice interleaving, flexible macro-block ordering (FMO), parameter set sharing, and error concealment techniques [3]. However, all these error resiliency schemes are APP layer schemes that do not consider physical (PHY) layer systems. There have been several previous works addressing APP-PHY cross layer design.

In the APP-PHY cross layer design approaches in [4] and [5], an orthogonal space-time block code (OSTBC) was adopted for multiple-input multiple-output (MIMO) systems [6]. The OSTBC MIMO system, however, does not increase data transmission speed when compared with the traditional single antenna PHY system [7]. Due to the low transmission speed, MIMO system using an OSTBC seems not suitable for real time video streaming.

In [8], an implicit unequal error protection (UEP) technique for video streaming over MIMO wireless channel was proposed. Spatially multiplexed (SM) MIMO system provides $N_{min} = \min(N_T, N_R)$ virtual subchannels, where N_T is the number of transmit antennas and N_R is the number of receive antennas, thereby N_{min} times higher data transmission speed than single antenna PHY system. When linear signal detection is used as in [8], the virtual subchannels show different transmission reliability, i.e, signal-to-noise ratio (SNR). In [8], UEP is achieved implicitly by assigning a APP video stream of higher priority to a PHY subchannel with higher reliability. In [9], a transmission power for multiple transmit antennas was also controlled to further benefit from MIMO systems. In these two previous works, however, linear signal detection methods were considered that offer severely degraded error performance when compared to a joint signal detection method.

In this paper, we propose an UEP technique for prioritized video streaming, assuming SM MIMO system with a suboptimal joint signal detection method QR-decomposition-least-reliable-layer (QR-LRL). There are various joint detection methods such as sphere decoding (SD) [10], QR-decomposition-M-algorithm-maximum likelihood detection (QRM-MLD) [11], lattice reduction aided detection (LRAD) [12], and optimal ML signal detection [13]. From the perspective of video streaming, the main problem of using joint signal detection is that all the signals from multiple antennas are jointly detected, thus the transmission reliability of all PHY subchannels are not differentiated. Consequently, UEP for prioritized video streaming exploiting the reliability information of subchannels is not allowed. In this paper, we show that the suboptimal joint detection method QR-LRL in [14] can be used for UEP. The QR-LRL is a computationally efficient but suboptimal joint detection method, thus the average BER performance is inferior to that of ML signal detection. The PSNR performance of QR-LRL, however,

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is slightly superior to that of the ML detection as will be demonstrated in the simulation section.

II. System Model

The developed APP-PHY cross layer system, illustrated in Fig. 1, is described in this section. The APP layer of the system is based on the H.264/AVC encoder, which delivers network abstraction layer (NAL) unit streams. In Fig. 1, $X_{f,s,m}, f = 1, 2, \cdots, F, s = 1, 2, \cdots, S, m = 1, 2, \cdots, M$ stands for the m-th macroblock in the s-th slice of the f-th frame, where F is the number of frames, S is the number of slices in a frame, and M is the number of macroblocks in a slice. The notation $\hat{X}_{f,s,m}$ in Fig. 1 denotes the compressed macroblock that is different from $X_{f,s,m}$ due to quantization in the process of compression. In this paper, a slice or a NAL packet was considered as a single PHY packet. Each PHY packet is 31-bit cyclic redundancy check (CRC) encoded. Then, when SM MIMO system is assumed, NAL units or PHY packets are assigned to transmit antennas of appropriate reliability. At the receiver side, N_T PHY packets are jointly detected. Then, the CRC parity bits are used to determine if each packet is received safely. The acknowledgement (ACK) or not ACK (NACK) information is passed to the APP layer. If NACK for a slice is received, the APP layer does not try to decode the slice but perform an error concealment for the slice. Transmission of sequence parameter set (SPS) and picture parameter set (PPS) NAL units are assumed error-free.

We consider MIMO systems with N_T transmit antennas and $N_R (\geq N_T)$ receive antennas. Let $\mathbf{x} = [x_1 \ x_2 \cdots x_{N_T}]^T$ denote the transmit signal vector, where $x_i, i = 1, 2, \ldots, N_T$ is the transmitted signal from the ith transmit antenna; $\mathbf{y} = [y_1 \ y_2 \cdots y_{N_R}]^T$ denotes the received signal vector, where $y_j, j = 1, 2, \ldots, N_R$ is the received signal at the jth receive antenna; $\mathbf{H}$ with dimension of $N_R \times N_T$ denotes the channel gain matrix, of which entry $h_{j,i}, j = 1, 2, \ldots, N_R, i = 1, 2, \ldots, N_T$ is the channel gain between the ith transmit antenna and the jth receive antenna; $\mathbf{z} = [z_1 \ z_2 \cdots z_{N_R}]^T$ denotes the noise vector, where $z_j, j = 1, 2, \ldots, N_R$ is assumed to be zero mean complex white Gaussian with variance of σ_z^2. Then the MIMO system can be described as follows.

$$\mathbf{y} = \sqrt{\frac{E_x}{N_T}} \mathbf{H}\mathbf{x} + \mathbf{z}. \tag{1}$$

In this paper, we assume independent and identically distributed (i.i.d.) Rayleigh fading channel gains, and ideal channel estimation at the receiver side.

III. Unequal Error Protection Using MIMO PHY Systems

In this section, two previous UEP techniques are described, and we propose a novel UEP technique exploiting SM MIMO systems with a suboptimal joint detection.

A. UEP Using OSTBC MIMO System

In [4] [5], the orthogonal space-time block code $\mathbf{G}_4$ in [6] was used assuming 4 transmit antennas, i.e., $N_T = 4$. Then, assuming 4 receive antennas, i.e., $N_R = 4$, and collecting the received signals during 4 symbol periods, the received signal matrix $\mathbf{Y} \in \mathbb{C}^{4\times 4}$ is expressed as

$$\mathbf{Y} = \sqrt{\frac{E_x}{3}} \mathbf{H}\mathbf{X}^{\mathrm{OSTBC}} + \mathbf{Z}. \tag{2}$$

where $y_{j,n}, j = 1, 2, 3, 4, n = 1, 2, 3, 4$, the (j, n)th entry of $\mathbf{Y}$, denotes the received signal at the jth receive antenna during the nth symbol period; the noise matrix $\mathbf{Z} \in \mathbb{C}^{4\times 4}$ is composed of entries $z_{j,n}, j = 1, 2, 3, 4, n = 1, 2, 3, 4$, that denotes the noise at the jth receive antenna during the nth symbol period; the space-time coded signal is given as

$$\mathbf{X}^{\mathrm{OSTBC}} = \begin{bmatrix} x_1 & -x_2^* & -x_3^* & 0 \\ x_2 & x_1^* & 0 & -x_3^* \\ x_3 & 0 & x_1^* & x_2^* \\ 0 & x_3 & -x_2 & x_1 \end{bmatrix}. \tag{3}$$

We note that the number 3 in (2) is due to the fact that signals are transmitted from only 3 antennas simultaneously, although $N_T = 4$. From the received signal matrix $\mathbf{Y}$ in (2), optimal ML signal detection of x_1 is performed via the following simple linear processing.

$$\begin{aligned} \tilde{x}_1 &= \sum_{j=1}^{4} \left\{ h_{j,1}^* y_{j,1} + h_{j,2} y_{j,2}^* + h_{j,3} y_{j,3}^* + h_{j,4}^* y_{j,4} \right\} \\ &= \sqrt{\frac{E_x}{3}} \|\mathbf{H}\|_F^2 x_1 + \\ &\quad \sum_{j=1}^{4} \left\{ h_{j,1}^* z_{j,1} + h_{j,2} z_{j,2}^* + h_{j,3} z_{j,3}^* + h_{j,4}^* z_{j,4} \right\} \end{aligned} \tag{4}$$

Dividing both sides of (4) with $\sqrt{\frac{E_x}{3}} \|\mathbf{H}\|_F^2$, we have the estimate $\hat{x}_1 = x_1 + \hat{z}_1$. The three noise term in (4) can be shown to be a complex Gaussian noise with the same variance of $\|\mathbf{H}\|_F^2 \sigma_z^2$. With similar linear processing produces $\hat{x}_s, s = 2, 3$ with the same noise variance. The SNR of the signal $\hat{x}_s$ or $\tilde{x}_s$ is given as

$$\mathrm{SNR}^{\mathrm{OSTBC}}{}_s = \frac{E_x \|\mathbf{H}\|_F^2}{3\sigma_z^2}, s = 1, 2, 3. \tag{5}$$

From (5), it can be seen that the SNR of the three signals are identical, consequently the SNR information can not be used to implement UEP. In [4][5], various combinations of QP, channel coding rate, and constellation size were assigned to video streams of different priorities. However, it was shown that the data transmission speed of OSTBC MIMO system is almost the same as or even lower than that of the traditional single input single output (SISO) systems [7]. Note that the data transmission speed for the space-time code

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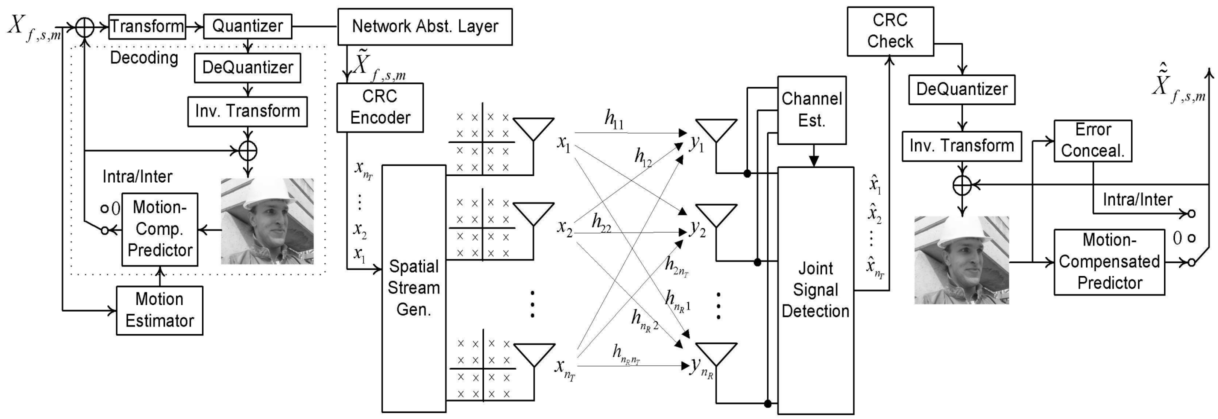

Figure 1. APP-PHY cross layer system.

$\mathbf{G}_4$ is $3/4$ symbols per channel use and that of SISO system is 1 symbol per channel use. We argue that the low data transmission speed of OSTBC MIMO system renders itself not suitable for video streaming service, which necessitates the SM MIMO system that is addressed in the following section.

B. UEP Using SM MIMO Systems with Linear Signal Detection

In [8][9], SM MIMO systems were used to provide UEP for prioritized video streaming. The considered detection methods in [8][9] are linear equalizers such as zero-forcing (ZF) or minimum mean squared error (MMSE) . If ZF or MMSE equalizer is used and when $N_T = N_R = 4$, the corresponding weight matrices are

$$\mathbf{W}_{\mathrm{ZF}} = \left(\mathbf{H}^H\mathbf{H}\right)^{-1}\mathbf{H}^H = \mathbf{H}^{-1} \tag{6}$$

$$\mathbf{W}_{\mathrm{MMSE}} = \left(\mathbf{H}^H\mathbf{H} + \frac{4\sigma_z^2}{E_x}\mathbf{I}_4\right)^{-1}\mathbf{H}^H \tag{7}$$

where $(\cdot)^H$ denotes the Hermitian transpose. The reliability of the sth signal (or the reliability of the corresponding subchannel),$s = 1, 2, 3, 4$, by the above two methods are derived as

$$\mathrm{SNR}^{\mathrm{ZF}}{}_s = \frac{E_x}{\|\mathbf{w}_{s,\mathrm{ZF}}\|^2 4\sigma_z^2}. \tag{8}$$

$$\mathrm{SINR}^{\mathrm{MMSE}}{}_s = \frac{|\mathbf{w}_{s,\mathrm{MMSE}}\mathbf{h}_s|^2}{\sum_{m\neq s}|\mathbf{w}_{m,\mathrm{MMSE}}\mathbf{h}_m|^2 + \|\mathbf{w}_{s,\mathrm{MMSE}}\|^2\frac{4\sigma_z^2}{E_x}}. \tag{9}$$

From (8) and (9), it can be seen that the reliability of the 4 subchannels are different. Let subch($r = s$) denote the sth most reliable subchannel, i.e., subchannel with the sth highest SNR or SINR. Exploiting this relationship, in [8] [9], a video stream of higher priority was assigned to a PHY subchannel with higher reliability to implement UEP implicitly. Note that the symbol transmission rate of the SM MIMO system is 4 symbols per channel use, that is much higher than that of single antenna system or OSTBC MIMO system.

Although the high transmission rate of SM MIMO systems with linear equalization is desirable, its BER performance is harshly degraded when compared to OSTBC MIMO systems. Fig. 2 compares the PER performance of OSTBC MIMO and SM MIMO with the linear MMSE detection. The linear MMSE detection was used rather than the ZF detection because the MMSE detection outperforms ZF detection in general. The size of PHY packet transmitted over each virtual subchannel of SM MIMO system is 5,000 bits. Considered constellation is a 16-QAM, thus a PHY packet is transmitted from its assigned transmit antenna for $5,000/4 = 1,250$ symbol periods. The PHY packet size of OSTBC MIMO system is 5,004 bits, thus a PHY packet is transmitted from 4 transmit antennas for $5,004/[4(3/4)] = 1,668$ symbol periods.

From Fig. 2, it can be observed that the pacekt error rate (PER) performance of SM MIMO systems with linear detection suffers from significantly degraded performance when compared to OSTBC MIMO system, and that the 4 subchannels in SM MIMO with linear detection show differentiated PER performance, i.e., differentiated reliabilities.

In order to retain the high transmission speed of SM MIMO systems and to achieve a good PER performance simultaneously, we propose to use SM MIMO system with joint signal detection that is discussed in the next section.

C. Proposed UEP Technique Using SM MIMO Systems with a Suboptimal Joint Detection

In this subsection, we propose a novel UEP technique for video streaming over SM MIMO systems with a suboptimal joint signal detection QR-LRL.

Maximum likelihood signal detection method that achieves the optimal PER performance is described as

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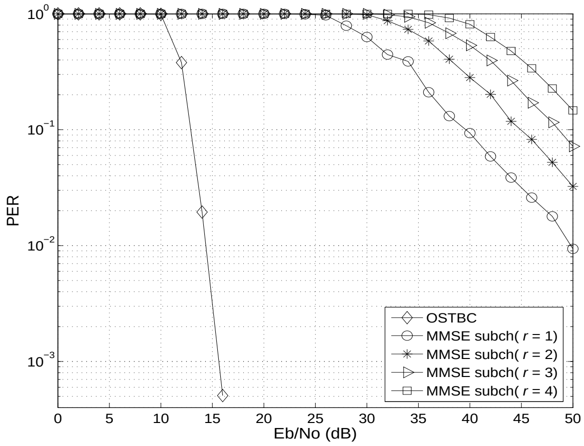

Figure 2. PER performance of OSTBC MIMO and SM MIMO with the linear MMSE detection.

$$\hat{\mathbf{x}}_{ML} = \arg\min_{\mathbf{x}\in\mathcal{C}^4} \left\| \mathbf{y} - \sqrt{\frac{E_x}{4}}\mathbf{H}\mathbf{x} \right\|^2 \quad (10)$$

where, $\mathcal{C}$ is the set of constellation points. The brute force implementation of the above ML signal detection searching over $|\mathcal{C}|^4$ vectors is almost impossible due to its required high computational complexity [13], where $|\mathcal{C}|$ denotes the cardinality of the argument set. SD method [10] is well known to achieve the ML performance with a significantly reduced average complexity, however, its complexity depends on the channel conditions and the worst case complexity is still high. There are also suboptimal signal detection methods such as QRM-MLD [11] and LRAD [12] methods that achieve near-ML performance. Although the implementation complexity of the aforementioned methods are significantly reduced and the optimal or a near-ML performance is achieved, PHY subchannels are not differentiated in terms of transmission reliability, not allowing the implementation of UEP.

In QR-LRL [14], the signals are ordered and detected sequentially, and the transmission reliability of the subchannels depend on the detection order. In QR-LRL, the most unreliable subchannel is selected using the SNR criterion (8).

$$s_{LRS} = \arg\min_{s\in\{1,2,3,4\}} \mathrm{SNR^{ZF}}_s. \quad (11)$$

All the constellation points are tried as the above selected symbol, and for each point as the selected symbol value, the remaining symbols are detected by the conventional VBLAST [15], producing a candidate vector set $\mathcal{S}_{\mathrm{QR-LRL}} = \{\mathbf{x}_c\}_{c=1}^{|\mathcal{C}|}$. The ML metrics are calculated for the candidate vectors to choose the most likely symbol vector as follows.

$$\hat{\mathbf{x}}_{\mathrm{QR-LRL}} = \arg\min_{\mathbf{x}\in\mathcal{S}_{\mathrm{QR-LRL}}} \left\| \mathbf{y} - \sqrt{\frac{E_x}{4}}\mathbf{H}\mathbf{x} \right\|^2 \quad (12)$$

We note that ML metrics are calculated for $|\mathcal{S}_{\mathrm{QR-LRL}}| = |\mathcal{C}|$ candidate vectors in (12), while $|\mathcal{C}|^4$ vectors are considered in (10). Trying all the constellation points as the first symbol, QR-LRL achieves almost the same BER performance as the conventional ML signal detection. Without loss of generality, we assume that the 3rd symbol has the minimum SNR. Obviously, the true signal vector has the smallest ML metric with high probability, hence the true signal vector is detected once it is included in the candidate vector set $\mathcal{S}_{\mathrm{QR-LRL}}$. Therefore, with high probability, the error happens when the true symbol vector is not contained in the candidate vector set. Since all the symbols are tried as x_3, error happens when true x_3 is tried but signal detection of the following system equation by VBLAST [15] is erroneous.

$$\underbrace{\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} - \sqrt{\frac{E_x}{4}}\mathbf{h}_3 x_3}_{\tilde{\mathbf{y}}} = \sqrt{\frac{E_x}{4}} \underbrace{[\mathbf{h}_1 \ \mathbf{h}_2 \ \mathbf{h}_4]}_{\tilde{\mathbf{H}}} \underbrace{\begin{bmatrix} x_1 \\ x_2 \\ x_4 \end{bmatrix}}_{\tilde{\mathbf{x}}} + \mathbf{z}. \quad (13)$$

where $\mathbf{h}_i$ is the ith column of the matrix $\mathbf{H}$ in (1).

It was shown that the condition number of above $\tilde{\mathbf{H}}$ is significantly reduced compared to $\mathbf{H}$ by choosing the least reliable symbol (LRS) by (11). Detection ordering of (13) is decided in the decreasing order of the following SNR.

$$\widetilde{\mathrm{SNR}}_s^{\mathrm{ZF}} = \frac{E_x}{\|\tilde{\mathbf{w}}_{s,\mathrm{ZF}}\|^2 4\sigma_z^2} \quad (14)$$

where, $\tilde{\mathbf{w}}_{s,\mathrm{ZF}}$ is the sth row vector of $(\tilde{\mathbf{H}}^H\tilde{\mathbf{H}})^{-1}\tilde{\mathbf{H}}^H$. The detection ordering is well known to reduce the error propagation effect [16], thereby increasing the probability that true $\mathbf{x}$ is contained in the set $\mathcal{S}_{\mathrm{QR-LRL}}$. Considering the criterion of choosing the first symbol as well as the criterion for ordering the remaining symbols, we can determine the reliability of the virtual 4 subchannels. The subchannel corresponding to the symbol chosen in (11) is the least reliable, which is denoted as subch($r = 4$). The subchannel for the first detected symbol in (13) is the most reliable, which is denoted as subch($r = 1$), the subchannels for the secondly and thirdly detected symbol using (13) are the second and third most reliable subchannels denoted as subch($r = 2$) and subch($r = 3$), respectively.

Fig. 3 shows that the average PER performance of QR-LRL is slightly worse than that of ML. Simulation environment is the same as in the simulations for Fig. 2. Note that the subch($r = 2$) achieves the optimal PER performance and that subch($r = 1$) outperforms the optimal ML detection. It can be also observed that the four subchannels of QR-LRL have differentiated transmission reliability.

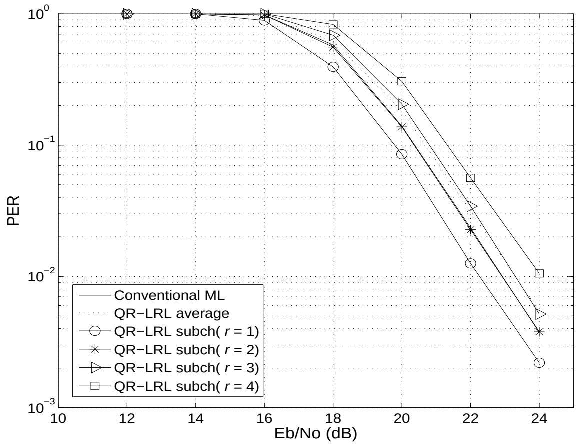

Figure 3. PER performance of the suboptimal QR-LRL and the conventional ML. The performance of conventional ML and QR-LRL subch($r = 2$) are almost identical. Also, the average PER of QR-LRL is almost the same as the QR-LRL subch($r = 3$).

IV. Simulation Results

In this section, we perform a set of computer simulations to show the improved PSNR performance by the proposed UEP technique based on QR-LRL. Reference software JM16.0 was used for encoding and decoding of H.264/AVC video stream. The total number of frames $F = 256$, GOP size is 4, 30 frames per second (fps) Foreman video in CIF resolution was used, the number of slices in a frame S=4, and a slice is composed of 99 macroblocks, IDR period and I period are the same as 4. QP of I and P slices are set as 28, and no B slice was used. The search range for motion vector estimation is ± 16 pixels with resolution of $1/4$ pixel, the number of reference frame for motion vector estimation was set to 1, entropy coding of CABAC was used. The transmission of the first GOP was also assumed error-free for a simple implementation of error concealment that copies a previous slice. In PHY layer, 16-QAM constellation was used, 31 bit CRC parity bits based on the polynomial $X^{31} + X^{30} + X^{26} + X^{24} + X^{18} + X^{15} + X^{14} + X^{12} + X^{11} + X^{10} + X^{8} + X^{6} + X^{5} + X^{4} + X^{3} + X + 1$ are used to check if a slice or a PHY pacekt was successfully received. If NACK is detected, the NACK information is passed to APP layer that does not try to decode but instead copy a recent slice.

Fig. 4 compares the PSNR performance of the two schemes at $E_b/N_0 = 22$(dB), the conventional ML and the suboptimal QR-LRL-based UEP. The PSNR in Fig. 4 is the average of 7 PSNRs for 7 different set of i.i.d. PHY channel gains and noises. It can be seen that the suboptimal QR-LRL-based UEP achieves a better performance than the conventional ML detection. Thus it can be stated that a better average PER performance does not guarantee a better PSNR performance. We note that the conventional optimal ML detection requires $|\mathcal{C}|^4$ times ML metric calculations, while the suboptimal QR-LRL requires only $|\mathcal{C}|$ times ML metric calculations.

V. Conclusion

In this paper, we proposed a novel UEP technique for prioritized video streaming over SM MIMO systems with a suboptimal joint detection. OSTBC MIMO system and SM MIMO system with linear signal detection suffer from a low data transmission speed and a degraded PER performance, respectively. SM MIMO system with joint detection achieves both high transmission speed and high transmission reliability, however, UEP is not allowed in general. We showed the suboptimal joint detection method QR-LRL can be used to implement UEP. With the aid of computer simulations, we demonstrated that the PSNR by the suboptimal QR-LRL, requiring only $|\mathcal{C}|$ times ML metric calculations, is slightly superior to that by the conventional optimal ML detection that requires $|\mathcal{C}|^4$ times ML metric calculations, when the number of transmit antenna is 4.

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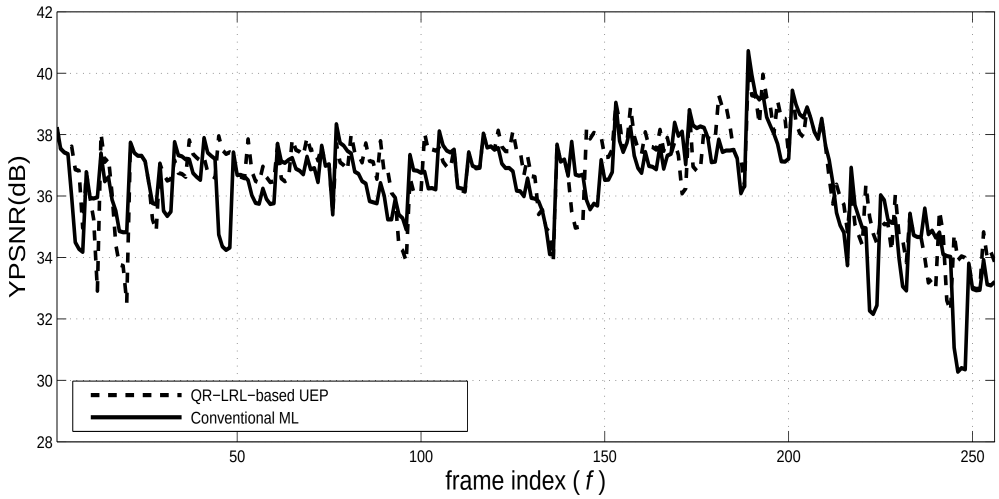

Figure 4. PSNR performance of the conventional ML and QR-LRL-based UEP.

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