LARGE-SCALE MIMO IS CAPABLE OF ELIMINATING POWER-THIRSTY CHANNEL CODING FOR WIRELESS TRANSMISSION OF HEVC/H.265 VIDEO

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ABSTRACT

A wireless video transmission architecture relying on the emerging LS-MIMO technique is proposed. Upon using the most advanced high efficiency video coding (also known as H.265), we demonstrate that the proposed architecture invoking the low-complexity linear zero-forcing detector and dispensing with any channel coding is capable of significantly outperforming the conventional small-scale MIMO-based architecture, even if the latter employs the high-complexity optimal maximum likelihood detector and a rate-1/3 recursive systematic convolutional channel codec. Specifically, compared to the conventional small-scale MIMO system, the effective system throughput of the proposed LS-MIMO-based scheme is increased by a factor of up to three, and the quality of reconstructed video quantified in terms of the PSNR is improved by about 22.5 dB at a channel SNR of $E_b/N_0 \approx 6$ dB for delay-tolerant video file delivery applications, and about 20 dB for lip-synchronized real-time interactive video applications. Alternatively, viewing the attainable improvement from a power-saving perspective, a channel SNR gain as high as $\Delta_{E_b/N_0} \approx 5$ dB is observed at a PSNR of 36 dB for the scenario of delay-tolerant video applications, and again, an even higher channel SNR gain is achieved in the real-time video application scenario. Therefore, we envisage that LS-MIMO-aided wireless multimedia communications is capable of dispensing with the power-thirsty channel codec altogether!

INTRODUCTION

The demand for video traffic in wireless networks is set to soar in the near future [1]. To support improved wireless video services, two major technological directions may be pursued: improving the video source compression efficiency and increasing the wireless channel capacity.

In the first direction, it has been shown [2, 3] that the emerging high efficiency video coding (HEVC/H.265) standard [4] is capable of significantly improving the video compression efficiency at a given reconstructed video quality compared to the existing H.264 standard [5, 6], albeit at the cost of increased computational complexity [2, 3]. However, increased compression efficiency usually makes the coded video stream more vulnerable to packet losses [3, 7]. The traditional approach of compensating this side effect is to employ sufficiently powerful error correction codes (ECCs), such as recursive systematic convolutional (RSC) codes, turbo codes, or low-density parity check (LDPC) codes for improving the bit/packet error rate (BER/PER) [7, 8]. Unfortunately, the redundant bits introduced by ECC not only require additional energy to transmit, which is a serious burden for low-power devices such as mobile terminals and wireless sensors, but also decrease the effective transmission rate of a system. For example, when a rate-1/3 ECC is used, the number of bits to be transmitted is three times as high as that of the system dispensing with ECC. *Therefore, how to strike an attractive trade-off among the transmission reliability, video transmission rate, and energy efficiency is an important research problem.*

In the second direction, as one of the key technologies for future fifth generation (5G) wireless communications, large-scale multiple-input multiple-output (LS-MIMO) techniques have been shown to be capable of providing substantial transmission rate, reliability, and/or energy efficiency improvements through the use of a large number of base station (BS) antennas [9–12].

Against the above background, in this article we present a new system architecture based on the interdisciplinary study of how to transmit HEVC/H.265 compressed video over wireless channels with the aid of LS-MIMO techniques. Our novel contributions are summarized as follows:

•We devise a low-complexity architecture for multipoint-to-point (M2P) H.265 video transmission relying on an uplink LS-MIMO system. Upon using a moderate number of BS antennas and a low-complexity linear zero forcing (ZF)

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LS-MIMO detector, we demonstrate that the proposed architecture, dispensing with any ECC, is capable of offering an improved performance in terms of both the achievable transmission rate and the reconstructed video quality compared to its traditional small-scale MIMO counterpart, which relies on both a sophisticated ECC codec and the optimal high-complexity maximum likelihood (ML) symbol detector.

•To the best of our knowledge, using LS-MIMOs for wirelessly transmitting the most advanced HEVC/H.265 video stream, which is traffic-demanding, has never been reported before in the open literature. Our results explicitly demonstrate that at the expense of an increased number of antenna elements and RF chains, our much simpler signal processing architecture is capable of significantly outperforming the higher-complexity, higher-delay, higher-energy-consumption traditional architecture. The significance of our results is that they potentially open up a new interdisciplinary research direction with the objective of identifying hitherto unexplored reduced-complexity system architectures, which are facilitated by cutting-edge LS-MIMO combined with the emerging HEVC/H.265 video processing.

A Case Study of the Benefits of LS-MIMO Systems

In order to demonstrate the benefits of LS-MIMOs, let us commence with a pair of parallel case studies concerning the BER performance of an uplink LS-MIMO system and of a traditional small-scale uplink MIMO system. The energy efficiency of both systems is also discussed.

Both systems are assumed to be synchronous and may be characterized by the classic MIMO system model of $\mathbf{y} = \mathbf{Hs} + \mathbf{n}$, where $\mathbf{y} \in \mathbb{C}^{N_r \times 1}$ is the signal vector received at the BS in each time instance; $\mathbf{H} \in \mathbb{C}^{N_r \times N_t}$ denotes the random wireless channel matrix between N_t single-antenna users and the BS equipped with N_r antennas; and $\mathbf{s} \in \mathbb{C}^{N_t \times 1}$ represents the symbol vector transmitted in each time instance, with elements s_i ($i = 1, 2,..., N_t$) being randomly taken from a modulation constellation $\mathbb{A}$ and satisfying the total transmit power constraint of $E(\|\mathbf{s}\|^2) = 1$. In other words, the total transmit power of all users at each time instance is assumed to be constant, and the transmit power of each single-antenna user in our LS-MIMO system is proportional to $1/N_t$. Additionally, $\mathbf{n} \in \mathbb{C}^{N_t \times 1}$ denotes the complex-valued additive white Gaussian noise (AWGN) vector, the elements of which obey the independent identically distributed (i.i.d) $\mathcal{CN}(0,2\sigma^2)$. We assume an uncorrelated flat Rayleigh fading channel, which implies that each entry of $\mathbf{H}$ (i.e., h_{ji}) is a complex-valued Gaussian variable. In order to ensure that the site-specific received signal-to-noise ratio (SNR) biases caused by large-scale fading such as path loss and shadowing are removed, the channel coefficients h_{ji} are normalized as $\mathcal{CN}(0,1)$.

The Advocated LS-MIMO Configuration

For the uplink LS-MIMO, $N_r \gg N_t$ is required. Hence, in the uplink LS-MIMO system considered, N_t was set to $N_t = \{2, 4, 6\}$, and N_r was set to the moderate value of 40, while in most of the LS-MIMO literature [9–12] hundreds of BS antennas are typically assumed. As a result, the uplink transmit power of each user in our LS-MIMO system becomes 1/2, 1/4, and 1/6 of the total transmit power, respectively. The low-complexity linear ZF-based MIMO detector of [12] was invoked at the BS, but no ECC was employed. The linear ZF detector is characterized by $\hat{\mathbf{s}} = \det(\mathbf{Wy})$, where $\det(\cdot)$ denotes the hard-decision detector implemented by a slicer, and we have $\mathbf{W} = (\mathbf{H}^H \mathbf{H})^{-1}\mathbf{H}^H$ for the scenario of $N_r > N_t$, while $\mathbf{W} = \mathbf{H}^{-1}$ if $N_r = N_t$.

Notably, for the uplink LS-MIMO systems it has been shown in [13] that when the number of BS antennas N_r is sufficiently large, the transmit power of each single-antenna user can be made proportional to $1/N_r$, provided that the BS has perfect knowledge of the channel state information (CSI) $\mathbf{H}$; alternatively, it becomes proportional to

$$1\Big/ \sqrt{N_r}$$

if $\mathbf{H}$ is estimated from the uplink pilots, with no performance degradation in both cases. This is indeed a more optimistic result than the $1/N_t$-power-scaling assumption we made above. Anyway, in LS-MIMO systems each antenna element uses an extremely low transmit power, which could be on the order of milliwatts. Nonetheless, in practice, several realistic imperfections will undoubtedly prevent us from fully realizing the above optimistic power savings, due to the associated CSI estimation errors, the interference imposed by other cells, and the additional RF front end circuitry. The undersized impact of these factors on the system's energy consumption is highly dependent on the specific system implementations, which is hence yet to be rigorously investigated. Even so, the prospect of saving an order of magnitude in transmit power is significant, because we can achieve improved system performance under the same regulatory power constraints, and because the escalating energy consumption of both the BSs and the users is a growing concern [10, 13, 14].

The Benchmark Small-Scale MIMO Configuration

Additionally, an RSC-aided conventional (4 × 4)-element small-scale spatial-multiplexing MIMO system was used as the benchmark. Therefore, the uplink transmit power of each user becomes 1/4, which indicates that both the per-user transmit power and the total transmit power of the two MIMO systems are comparable. The generator polynomials of [133, 165, 171]$_8$ represented in octal form were employed for configuring the rate-1/3 RSC code, which was decoded at the receiver by the classic soft-output Viterbi algorithm. Additionally, the optimal ML-based MIMO detector of [12] was used, which relies on a high-complexity "brute force search" formulated as

$$\hat{\mathbf{s}} = \arg \min_{\mathbf{s} \in \mathbb{A}^{N_t}} \left\| \mathbf{y} - \mathbf{Hs} \right\|^2 .$$

Note that no iteration was imposed between the MIMO detector and the channel decoder.

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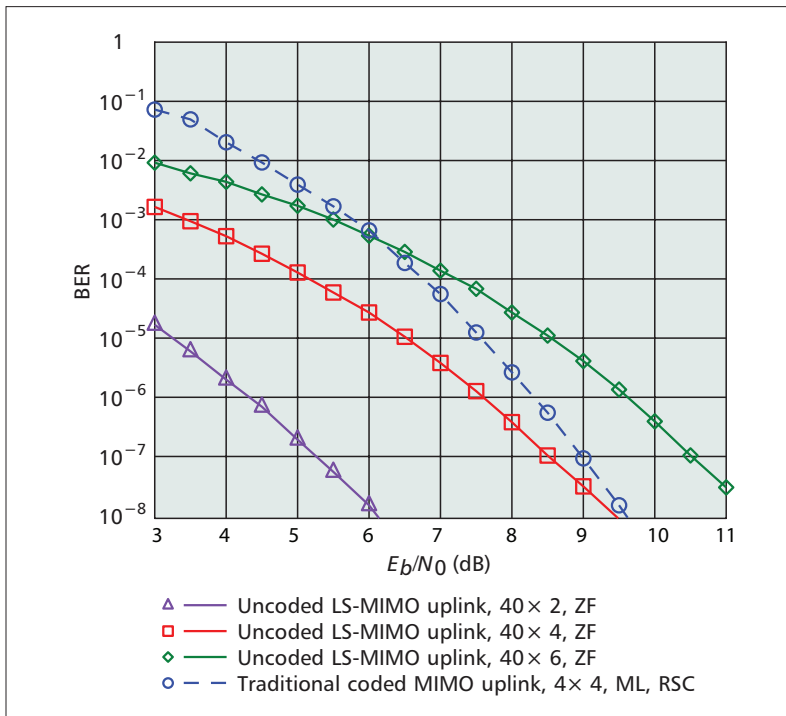
Figure 1. BER vs. the channel SNR E_b/N_0 for an uncorrelated flat Rayleigh fading channel.

We assume that quadrature amplitude modulation (QAM) signals were transmitted in both systems. In Fig. 1 we present the BER vs. E_b/N_0 performance of both systems invoking 4-QAM. Observe from Fig. 1 that the BER performance of our uncoded uplink LS-MIMO system becomes even better than that of the RSC-aided traditional small-scale MIMO system when N_t of the former scheme is no more than 4.

Compared to that of the small-scale MIMO benchmark system, the energy consumption of the signal processing at the LS-MIMO scheme's transceiver is expected to be significantly reduced, since the high-complexity channel codec is eliminated and the MIMO detector is the low-complexity ZF detector. In contrast, the small-scale MIMO benchmark considered has to use a sophisticated channel codec and the optimal ML MIMO detector, which consumes more power and imposes a higher delay, but only provides less attractive overall performance.

THE PROPOSED VIDEO TRANSMISSION SYSTEM ARCHITECTURE

Based on the above numerical evaluation of the BER performance as well as the discussions concerning the energy efficiency of the two MIMO configurations, in this section we propose a low-complexity M2P video transmission architecture relying on the uplink LS-MIMO system shown in Fig. 2.

At the transmit side, a standard video encoder, such as H.264 [5, 6] or H.265 [2–4], may first be invoked at each user for video compression. Then the output video streams of the video encoders are segmented into packets of different size for transport over IP networks. In a common M2P wireless video transmission scenario, such

as mobile video capture or multipoint wireless video monitoring, the users typically have a similar transmit power and rate. Therefore, with only a marginal loss of throughput, at the transmit side of the proposed architecture of Fig. 2 we use a zero-padding-aided packet synchronization mechanism, where a variable number of zeros are appended to the shorter packets, after completing the video encoding and packet segmentation. Explicitly, for packets of different size, the number of zeros appended by the zero-padding operation is different so that after completing the zero-padding operation, all the packets would have the same size. This mechanism is capable of aligning video packets and synchronizing the transmissions of multiple users. The bits in these aligned packets are then transmitted as QAM signals.

At the receive side, first a MIMO detector is used to recover the transmitted QAM symbols, which are then fed into QAM demodulators in order to obtain the bitstreams of each user. The zeros appended to the shorter packets are removed, and the resultant packets are combined to generate the original video streams. Finally, these video streams are fed into the video decoders of Fig. 2, recovering the original video content of each user.

For the small-scale MIMO benchmark system, there will be a channel encoder immediately after the packet segmentation operation and correspondingly a channel decoder counterpart immediately before the video decoder.

PERFORMANCE EVALUATION OF HEVC/H.265 VIDEO TRANSMISSION

In this section, we benchmark the performance of the proposed LS-MIMO-aided wireless video transmission system against that of the traditional small-scale-MIMO-assisted wireless video transmission system in Figs. 3 and 4.

PEAK SIGNAL-TO-NOISE RATIO PERFORMANCE COMPARISON

To benchmark the performance of the proposed LS-MIMO system against the traditional small-scale MIMO system, four Class D [416 × 240 @30 Hz] test sequences (Keiba, RaceHorses, Flowervase, and Mobisode2) as required by the HEVC/H.265 evaluation [15] are invoked, each of which is transmitted by one of the four uplink users supported. All these standard sequences are provided by the Joint Collaborative Team on Video Coding (JCT-VC) expert group [4, 15]. All sequences associated with different texture characteristics and motion activities are encoded using the HEVC/H.265 reference software (HM v. 13.1) [15], assuming a frame rate of 30 fps, 200 frames, and random access coding mode.

Two scenarios are considered, since the transmission delay and source video quality constitute a pair of conflicting metrics to be traded off against each other for a given wireless transmission rate. First, when the same target video bit rate of 600 kb/s is assumed for both schemes, implying that the quality of the input video streams for both schemes is the same, the error-
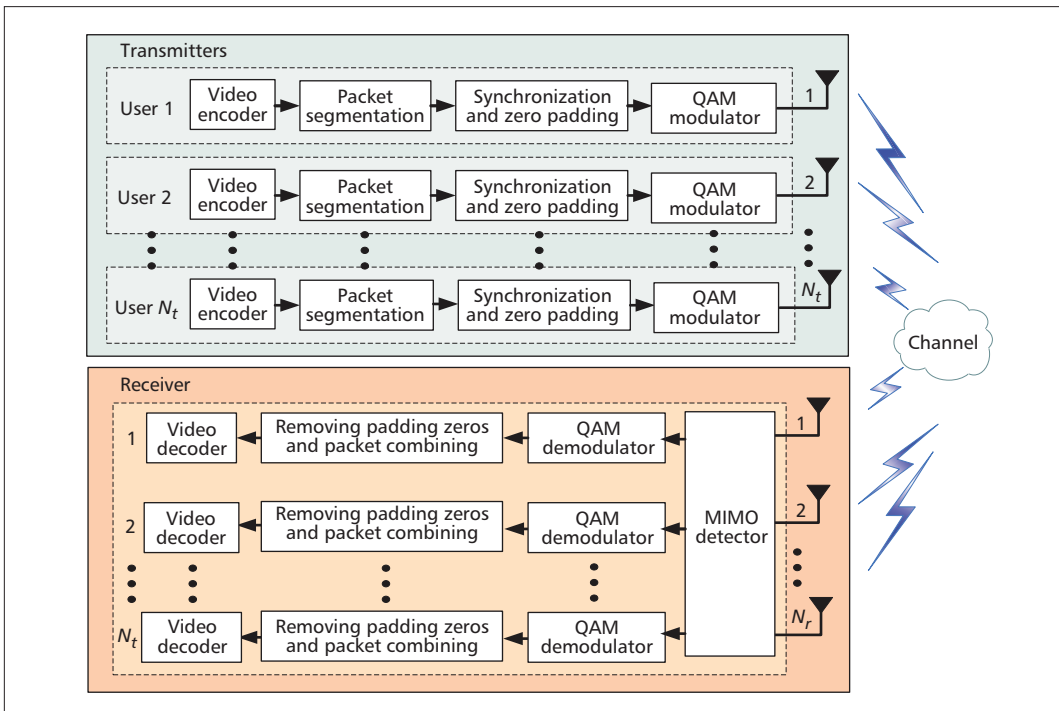
Figure 2. The proposed wireless video transmission architecture relying on LS-MIMO, where we have $N_r \gg N_t$.

At the receiver, each channel-decoded/ MIMO-detected NALU failing to pass the CRC process is removed during the packet combining process (i.e., prior to the video decoding). Then each adjusted bitstream belonging to different users is sent to the individual video decoders, respectively.

free peak SNR (PSNR) (Y component) of the above-mentioned four test sequences are 40.22, 35.19, 48.89, and 49.92 dB, respectively, as seen in Fig. 3. For the (40×4)-element LS-MIMO system and the (4×4)-element conventional small-scale MIMO system that have the same *raw transmission rate* in terms of the MIMO link, the transmission delay imposed by the conventional small-scale MIMO system may be three times as high as that of the proposed LS-MIMO system, because the 1/3-rate RSC results in a threefold file size increase. Therefore, this scenario is suitable for delay-tolerant video file delivery applications, such as high-definition film downloading/uploading. Note that the "three times transmission delay" is estimated relying on the assumption that the processing delay per bit at the receivers of both systems is the same. However, as mentioned above, the receiver of the channel-coded small-scale MIMO benchmark system may have higher computational complexity than our uncoded LS-MIMO scheme. Therefore, in practice, the transmission delay of the channel-coded small-scale MIMO benchmark system may be even higher than three times. On the other hand, for delay-sensitive interactive video applications, such as live video streaming, the delay specifications of the two systems are expected to be the same. In this case, the quality of the source video of the conventional 1/3-rate RSC-coded small-scale MIMO system considered has to be degraded; hence, the source video bit rate has to be reduced to 200 kb/s, which translates to the error-free PSNR (Y component) of 34.35, 30.25, 45.21, and 47.80 dB for the four test sequences considered, respectively, as observed from Fig. 3.

All video bitstreams obtained from the HEVC encoder are in the form of network abstract layer units (NALUs), which are transmitted on an NALU basis as well. The NALU packets belonging to the same user maintain their natural chronological order. Each user has one NALU packet to be transmitted during each transmission interval, and these packets are aligned in time to form a transmission block, which facilitates parallel transmission using the advocated MIMO scheme. Moreover, each NALU is protected by cyclic redundancy check (CRC) codes, the official implementation of which is given in the reference software (HM v.13.1) [15]. We note that in video communications, typically CRC codes are used for detecting whether a bitstream is error-free or not at the output of the channel decoder. This feature is supported by most video compression standards, such as H.264/advanced video coding (AVC) [5, 6] and H.265/HEVC [2–4, 15]. At the receiver, each channel-decoded/ MIMO-detected NALU failing to pass the CRC process is removed during the packet combining process (i.e., prior to the video decoding). Then each adjusted bitstream belonging to different users is sent to the individual video decoders, respectively, as shown in Fig. 2.

Additionally, a video frame-copy-based two-stage error concealment mechanism is also invoked at the receiver. The reference codec of the previous video compression standard H.264/ AVC provides an error concealment feature [5], which uses frame substitution for all the lost video pictures automatically. Unfortunately, this is no longer the case in the H.265/HEVC development [2–4, 15]. Our investigations carried out in this article show that the H.265/HEVC codec only supports a basic level of error concealment. When an NALU packet containing a video picture is lost, the H.265/HEVC video decoder first attempts to conceal the picture loss by using its preceding reference picture as a direct frame copy. But if the reference picture is not

in the decoded picture buffer (DPB), the decoder becomes incapable of filling the lost picture. This indicates that not all the lost video pictures can be replenished by the H.265/HEVC video decoder. Therefore, a further complementary error concealment mechanism is implemented in the systems considered. More specifically, the lost pictures that cannot be replenished by the video decoder itself are filled in by using another frame-copy-based error concealment mechanism, which copies the closest video picture in time instead of the reference picture to replace the lost picture. As a beneficial result, this two-stage error concealment mechanism is able to replenish all the lost pictures in the video decoding module. In all of our experiments, each video bitstream is transmitted 2000 times in order to generate statistically sound performance results.

More specifically, the PSNR vs. E_b/N_0 (i.e., channel SNR) performance of both the proposed LS-MIMO-aided wireless video transmission system and the traditional small-scale MIMO-assisted wireless video transmission system is presented in Fig. 3, where we observe that the proposed system substantially outperforms the traditional system, despite using no ECC for both the delay-tolerant and real-time interactive video applications. Let us consider the Keiba sequence as an example. We can see that in terms of its video quality improvement the proposed scheme outperforms the traditional scheme by about $\Delta_{PSNR} \approx 22.5$ dB at an $E_b/N_0 = 6$ dB for a video
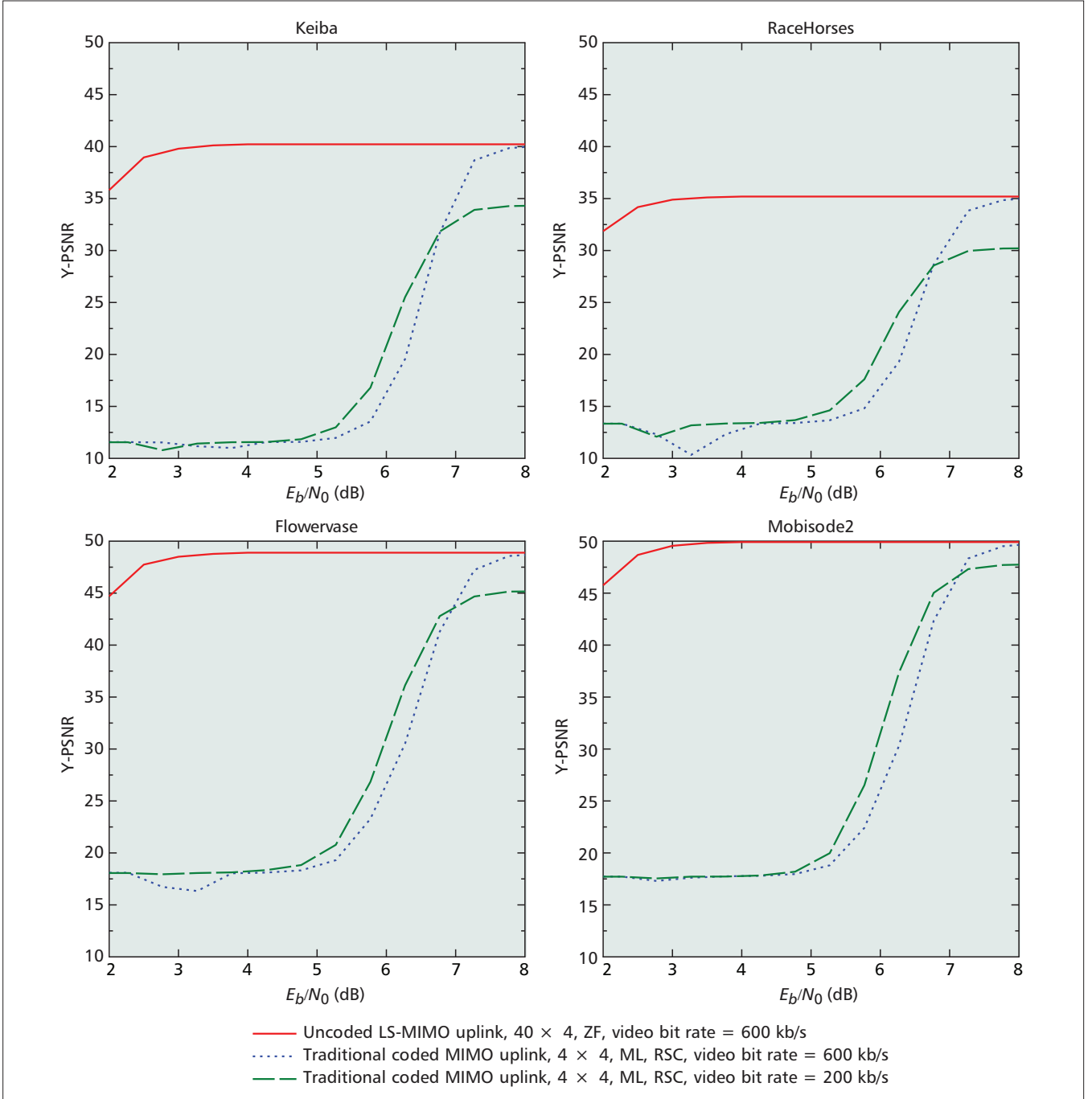

Figure 3. PSNR vs. the channel SNR E_b/N_0.

bit rate of 600 kb/s (delay-tolerant video download applications), and about $\Delta_{PSNR} \approx 20$ dB at an $E_b/N_0 = 6$ dB for a video bit rate of 200 kb/s (real-time lip-synchronized video applications). Alternatively, a channel SNR gain of $\Delta_{E_b/N_0} \approx 5$ dB is observed at a video PSNR of 36 dB for the video bit rate of 600 kb/s. Again, an even higher channel SNR gain is achieved in the real-time lip-synchronized video application scenario, where the video bit rate of the conventional benchmarking scheme is 200 kb/s.

It should be noted that in the scenario of having a video bit rate of 600 kb/s, both systems have a similar PSNR vs. channel SNR performance in the high-SNR region. This is due to the fact that the NALU PER is extremely low in the high-SNR scenario in both systems. However, for the scenario of real-time video applications, the PSNR achieved by the proposed LS-MIMO scheme is higher than that of the conventional small-scale coded MIMO scheme. This is because the video bit rate of the proposed LS-MIMO scheme is 600 kb/s, while the conventional small-scale MIMO scheme exhibiting the same transmission delay has a video bit rate of 200 kb/s.

Throughput Performance Comparison

For further demonstration of the performance discrepancy between the two systems, let us calculate the attainable throughput using the parameters of a 4-QAM-based Long Term Evolution (LTE)-like system, as shown in Table 1 (see J. Zyren and W. McCoy, "Overview of the 3GPP Long Term Evolution Physical Layer," Freescale Semiconductor, Inc., July 2007 for more details). The theoretical raw throughput of the systems assuming perfectly error-free channel decoding may be formulated based on the resource block (RB) and frame structure defined in LTE as follows:

$$C_{raw} = \frac{M_b \times M_{spts} \times M_{RB} \times M_f \times N_t \times R_c}{T_{ts}}, \quad (1)$$

where the channel coding rate is set to $R_c = 1$ in the proposed system, since no channel codec is used. To be more specific, Eq. 1 is essentially the number of information bits transmitted in a time slot divided by the duration of the time slot. Relying on Eq. 1, the theoretical raw throughput bound of the proposed uncoded LS-MIMO system is $C_{raw,LS} = 134.4$ Mb/s. By contrast, the theoretical bound of the raw throughput of the conventional benchmark MIMO system using a rate-1/3 channel codec is $C_{raw,B} = 44.8$ Mb/s. In other words, the theoretical raw throughput of the proposed scheme is three times as high as that of the benchmark scheme.

For the sake of visualizing the achievable effective throughput of the two systems, we define $\text{BER}_{PPR}(E_b/N_0)$ as the post-packet-recovery (PPR) error rate, which is calculated as

$$\text{BER}_{PPR}\left(E_b/N_0\right) = \frac{N_{b,PPR}}{N_{b,t}}, \quad (2)$$

where $N_{b,PPR}$ is the total number of erroneous bits after PPR, while $N_{b,t}$ is the total number of bits transmitted by the four users supported. Therefore, the achievable effective throughput of

Parameters	Value
Bits per modulation symbol	$M_b = \log_2 M = 2$
Number of transmit antennas	$N_t = 4$
Number of receive antennas	$N_r = \{4, 40\}$
Duration per time slot	$T_{ts} = 0.5$ ms
Number of orthogonal frequency-division multiplexing (OFDM) symbols per time slot	$M_{spts} = 7$
Total bandwidth	$B = 20$ MHz
Total number of resource blocks (RBs) for data transmission per time slot	$M_{RB} = 100$
Number of subcarriers per RB	$M_f = 12$
Channel coding rate	$R_c = \{1, 1/3\}$

Table 1. Parameters of an LTE-like system using 4-QAM.

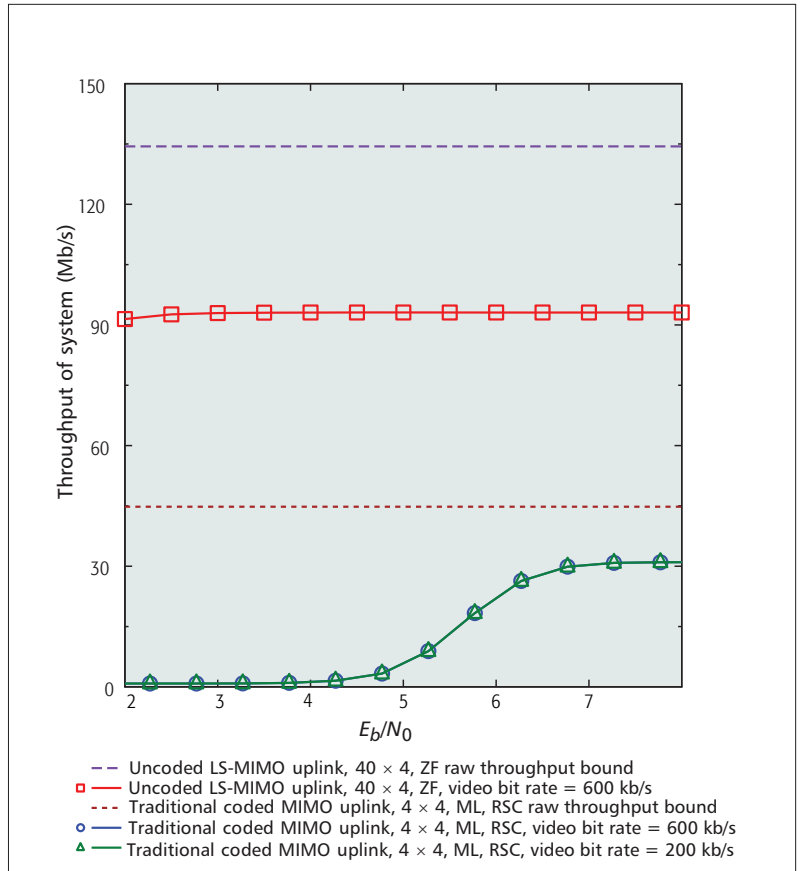**Figure 4.** Throughput vs. the channel SNR E_b/N_0.

both systems is given by

$$C_{eff}(E_b/N_0) = C_{raw} \times [1 - \text{BER}_{PPR}(E_b/N_0)]. \quad (3)$$

Finally, the achievable effective throughput of the proposed architecture and that of the conventional benchmark architecture are shown in Fig. 4. Observe in Fig. 4 that neither of the

We demonstrate that for the most advanced HEVC/H.265 video codec, the proposed architecture invoking the low-complexity linear ZF detector and no channel coding may substantially outperform the conventional small-scale MIMO based architecture employing the high-complexity optimal ML detector and a rate-1/3 RSC codec.

systems are capable of reaching the theoretical bound. The reasons for this observation are that both systems suffer from channel-induced transmission errors, and about 30 bits are wasted in the zero padding of each NALU in the proposed scheme. However, the effective throughput of the proposed scheme is still at least three times as high as that of the benchmark system at most channel SNR values of interest, which is primarily because the latter invokes a rate-1/3 channel codec. Additionally, it is worth noting that the achievable effective throughput of the benchmark system supporting the video bit rates of 600 kb/s and 200 kb/s remains identical, which is because the transmission capability of a wireless communication system is independent of the information source.

CONCLUSIONS

In this article, a transmission architecture relying on the emerging large-scale MIMO technique is proposed for future wireless video communications. We demonstrate that for the most advanced HEVC/H.265 video codec, the proposed architecture invoking the low-complexity linear ZF detector and no channel coding may substantially outperform the conventional small-scale-MIMO-based architecture employing the high-complexity optimal ML detector and a rate-1/3 RSC codec in terms of the achievable effective throughput as well as in terms of the reconstructed video quality (PSNR) for both delay-tolerant and real-time video applications.

ACKNOWLEDGMENT

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