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Channel adaptive rate control for energy optimization*

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Abstract: Low energy consumption is one of the main challenges for wireless video transmission on battery limited devices. The energy invested at the lower layers of the protocol stack involved in data communication, such as link and physical layer, represent an important part of the total energy consumption. This communication energy highly depends on the channel conditions and on the transmission data rate. Traditionally, video coding is unaware of varying channel conditions. In this paper, we propose a cross-layer approach in which the rate control mechanism of the video codec becomes channel-aware and steers the instantaneous output rate according to the channel conditions to reduce the communication energy. Our results show that energy savings of up to 30% can be obtained with a reduction of barely 0.1 dB on the average video quality. The impact of feedback delays is shown to be small. In addition, this adaptive mechanism has low complexity, which makes it suitable for real-time applications.

Key words: Rate control, Channel condition, Communication energy
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INTRODUCTION

Video transmission over wireless communication systems, where energy is a limited resource, faces the challenge to achieve the required performance at minimal energy consumption. Moreover, the negative impact of channel errors on the perceptual video quality makes the transmission over error-prone channels even more challenging. To combat the effect of channel losses, error protection and concealment strategies are applied at the codec, as well as the network and lower layers [Forward Error Correction (FEC), Automatic Repeat Request (ARQ), channel coding, etc].

The encoder, steered by the rate control (RC) mechanism, produces a data bit rate which is passed to lower communication layers (network, link and physical layers). The energy invested at the lower layers to guarantee a successful delivery, is highly dependent on both the channel conditions and on the amount of bits transmitted during varying conditions. The worse the channel conditions are, the higher the energy invested per bit is. Consequently, the more bits are transmitted, the higher the energy consumption is.

We present a cross-layer approach in which the video codec becomes network aware in order to decrease the communication energy. The channel conditions are fedback to the RC mechanism of the encoder that steers the output rate accordingly. Under bad channel conditions, when the communication energy per bit is high, the RC reduces the output rate to save energy. On the contrary, if the channel conditions are good, communication energy is low, and the channel-adaptive RC steers the encoder to a higher instantaneous output rate, while the average target bit rate and video quality are maintained.

In (Chandramouli *et al*., 2004; Hsu *et al*., 1999; Krunz and Hassan, 2004) optimized rate control strategies adapt to models of time varying channels. These studies focus on the impact of delay constraints on the end video quality. In (Hsu *et al*., 1999) the rate

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constrains are derived from the channel model using complex Rate Distortion optimization techniques more suited for scenarios with longer end-to-end delay, yielding both *PSNR* increases and reduced packet error rate. In (Chandramouli *et al*., 2004) a learning mechanism adapts the rate to the channel bit error rate. Packet errors are not considered and no impact of the feedback delay or algorithm complexity is given. In (Krunz and Hassan, 2004) hybrid ARQ/FEC schemes are used together with joint source/channel coding with the receiver signaling to the transmitter the frame size scaling needed to meet the time constraints.

These studies focus on video adaptation to meet delay constraints arising from the channel conditions. The complexity of the algorithms proposed imposes constraints on the video coding and makes them unsuitable for low complexity low delay real time applications. Finally, critical issues such as the impact on the communication energy are not addressed.

Our study focuses on the energy consumption during video transmission and aims at reducing the communication energy by adapting the codec output rate to the channel conditions. Moreover, our approach can be realized at real-time as it has low complexity incurring in no additional delay. This makes it suitable for low complexity low delay video applications, where energy consumption becomes a critical issue.

The remainder of this paper is structured as follows. Section 2 introduces the network models and Section 3 presents the channel-adaptive RC mechanism, based on the current MPEG-4 RC (Chiang and Zhang, 1997). In Section 4 results and analysis are given showing the energy savings achieved by the RC approach. Finally, some conclusions are drawn in Section 5.

NETWORK MODELLING

The following subsections present the channel modelling used as well as the model of communication energy involved in video transmission.

Channel modelling

We assume a wireless environment with a feedback channel where a priori probabilistic model of the channel behavior is available at the encoder. The burst-error wireless channel is modeled with an 8-state Markov model (Mangharam *et al*., 2005). Based on experiments for indoor WLAN (ETSI, 1998) we take a channel coherence time of 120 ms. That is, the channel remains constant for 3 or 4 video frames of the video sequence (encoded at 25 or 30 frames per second), while the RC mechanism adapts on a frame time basis.

Energy modelling in the wireless network

We use the energy models developed in (Mangharam *et al*., 2005) where expressions for the packet error rate (PER), energy and transmission time for each packet are derived taking into account the 802.11e MAC protocol and the above mentioned 8-state Markov channel model. The model assumes a scalable 802.11a physical layer, where it is possible to adapt the modem configuration to the current environment and traffic demands. It is out of the scope of this paper to fully describe the energy modelling performed in (Mangharam *et al*., 2005) but the readers can refer to the paper for the full details.

For simplicity, we assume only a single user on the considered wireless link. The overhead considered for the energy modelling is hence only the header and retransmissions overhead. No congestion is considered for a single MPEG-4 user over a 54 Mbps WLAN link. We hence focus, for each channel state, on the expected energy per bit for a certain targetted packet error rate (PER) as function of the 802.11a modem settings as described in (Mangharam *et al*., 2005). Fig.1 shows the energy per bit vs *PER* curves for channel states (CSs) 1 and 5, and different MAC packet sizes (PSs).

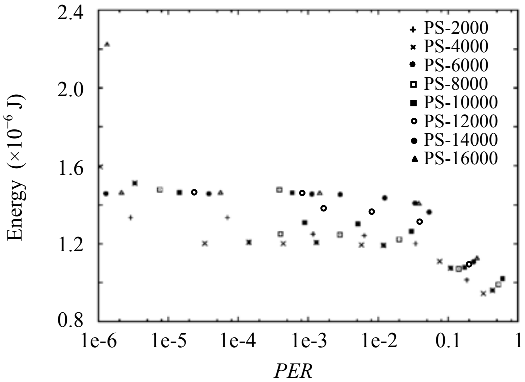

Fig.1 Energy per bit vs *PER* curve for channel state 5

Each point represents a specific configuration of the control settings $K_{i,j}$ for user *i* and *j* control knobs, for a given wireless LAN architecture, such as modulation, code rate, …, etc.

Only the discrete points can be allocated in practical communication links. Configuration points can be determined at the design time (or during a calibration step) of the transceiver. Simulations are carried out using verified energy-performance models on the ns-2 simulator (http://www.isi.edu/nsnam/ns/). We retain for each channel state (CS) a single representative energy-*PER* configuration point, to be used for the results in the remainder of this paper. We select for each CS the point with the lowest energy consumption, subject to a very low *PER* constraint (near to error-free quality), as we want to see how the required energy scales with channel conditions. The global communication energy is extracted from this expected energy per bit per CS as follows:

$$TotalEnergy = \sum_{i=1}^{8} R_i E_i, \tag{1}$$

where R_i is the amount of bits transmitted during CS *i* and E_i is the expected energy per bit for CS *i*.

The operation points taken from the energy-*PER* curves are selected from the optimal trade-off curve where the lowest energy is spent for a certain *PER* and for a very low *PER* to assume near to error-free quality. The MAC packet size is taken to be 8000 bits for all channel states. Table 1 gives the occurrence probability and energy per bit in Joules for each CS. CS 1 corresponds to the best channel conditions while CS 8 to the worst ones.

Table 1 shows that the required energy per bit dramatically increases when channel conditions get worse. Bad CSs (5 to 8) with a low occurrence probability (around 8% alltogether), can actually be responsible for roughly 50% of the energy consumption at the network side. The actual energy value depends both on the amount of bits coming from the application and on the current CS. This highlights the need for a channel aware video coder that produces an amount of bits according to the current channel conditions.

Table 1 CS probabilities and associated energy per bit

CS	Pr	Energy per bit
1	18.6	1
2	33.6	1.5
3	25.8	2.6
4	13.4	5
5	4.8	15
6	1.8	25
7	0.8	45
8	1.2	45

RATE CONTROL MECHANISM

The use of the RC mechanism typically flattens the overall bit rate variation. However, the frame size variations between consecutive frames are still high (factor of 2 or 3). As the RC mechanism is network unaware, peaks in the frame sizes can coincide with bad channel conditions in the network. During these bad CSs the communication energy invested per transmitted bit increases highly.

If an RC mechanism steers the instantaneous output video rate according to the network conditions, the network effort can be alleviated. Thus, by reducing the amount of bits to be transmitted during bad channel conditions the communication energy is reduced. Similarly, under good channel conditions where the network energy per bit required is much lower, the RC increases the output bit rate to profit from the good network condition.

Fig.2 shows a sequence of CS from the model given in (Mangharam *et al.*, 2005). Fig.3 shows the size of the frames produced by the normal RC (dashed line) and by the channel adaptive RC (solid line).

The standard RC mechanism allocates bits without considering current channel conditions. This way, big frames may be transmitted during bad CS, when the energy invested per bit needs to be high. On

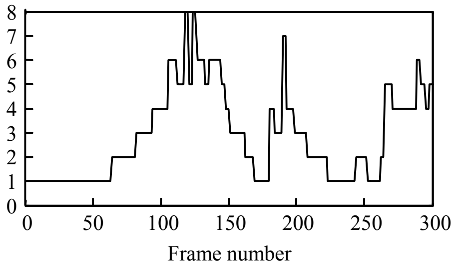

Fig.2 Channel state sequence

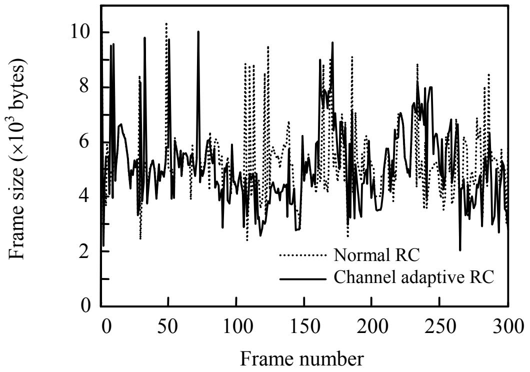

Fig.3 Frame sizes generated

the contrary, the adaptive RC generates bigger frames during good CS and smaller frames during bad CS. The bit rate peaks of the normal RC during bad CS, are then reduced while bigger frame sizes (rate peaks) are generated during the good channel conditions.

The following section deals with the algorithm modifications on the RC mechanism of MPEG-4 (ISO/IEC JTC1/SC29/WG11, 2001) to make RC become channel-adaptive.

Channel-adaptive rate control mechanism

The RC mechanism is aimed at determining the number of bits allocated per frame in order to meet an overall target bit rate. In the channel-adaptive RC the bit allocation per frame is done based on the CS under which the frame is sent. Our RC approach follows the same steps as the standard RC (Chiang and Zhang, 1997):

1. Variable initialization

Based on the overall target bit rate, target frame sizes are estimated for every kind of frame (I, P and B). In our adaptive RC we classify frames according to the channel condition during which they are sent. We estimate the number of frames under each CS *i* as:

$$num\_P\_Frame\_i = num\_P\_Frame\_Total \times Pr\_i, \quad (2)$$

where Pr_i is the CS probability and $num\_P\_Frame\_Total$ is the number of frames considered during the initialization (in our experiments 300 frames). In practice, the model probabilities could be re-estimated from channel measurements and used to reinitialize these variables every certain number of video frames.

While preserving the overall target bit rate, we compute initial target frame sizes in bits (Eq.(3)) for frames transmitted under different CS as a scaled version of the hypothetical average frame size (Eq.(4)):

$$AverFrameSize = Total\_bit\_rate / frame\_rate, \quad (3)$$

$$AverFrameSize\_i = AverFrameSize \times Factor\_i. \quad (4)$$

The scaling factor is smaller than 1 for bad channels so as to reduce the produced bits during bad conditions and slightly bigger than 1 during good channel conditions. To maintain the overall target bit rate, the scaling factor for the best channel *k* condition is adjusted based on the rest of the scaling factors:

$$bit\_rate\_k = Total\_bit\_rate - \sum(bit\_rate\_i), \quad i <> j, \quad (5)$$

$$Factor\_k = bit\_rate\_k / (num\_Frame\_k \times AverFrameSize). \quad (6)$$

The initial target bit rate per group of frames transmitted under CS *i* is estimated as:

$$bit\_rate\_i = num\_Frame\_i \times (AverFrameSize\_i). \quad (7)$$

After this initialization, the current CS is measured and fedback to the encoder, which applies the corresponding initial target frame size for that channel to the current frame.

2. Computation of quantization parameter

As in the standard RC and according to the Video Buffer Verifying (VBV) model (ISO/IEC JTC1/SC29/WG11, 2001), the QP of the current frame is computed based on the target frame size, QP and MAD (mean absolute difference) of the previous frame.

3. Rate distortion model update

Once the QP is selected, the frame is encoded and the R-D model is updated prior to the encoding of the next frame. Re-computation of variables is performed as in the standard RC (Chiang and Zhang, 1997). To steer the output bit rate, in addition to QP variation, our approach uses frame skipping, as also allowed in the MPEG-4 coding scheme (ISO/IEC JTC1/SC29/WG11, 2001). During the worst channel conditions (CSs 7 and 8) the frame rate is reduced to produce less bits. As this occurs with very low probability (around 2% of the time) the frame rate is only slightly reduced from 30 frames per second (fps) to around 29 fps.

Impact on video quality

On one hand, the frame size reduction and frame skipping during bad CS slightly degrades the video quality. Nevertheless this degradation is limited to a small percentage of time (due to 2% probability of bad channel states as 7 or 8). In addition, the scaling factor applied is also used to limit the degradation.

On the other hand, the bit reduction allows saving energy when the transmission is more costly. Moreover, more bandwidth becomes available for error protection or retransmissions, which can reduce the packet error rate (PER) and yield a better end quality. Usually, it is preferable to allow higher coding distortion with no *PER* than a higher *PER*.

Frames size reduction during bad channel conditions causes a small quality decrease (quality increase during good channel conditions). Frame quality variations stay in any case within the range of variations that occur with current RC approaches. In the standard RC variations where even 7 dB can be observed along the sequence with frequent variations of 2 or 3 dB between consecutive frames. The average *PSNR* decrease corresponding to the adaptive RC in Fig.3 is barely 0.2 dB. The impact in terms of motion jerkiness has been visually assessed to be minimal and the average frame rate is very slightly reduced. However the gain in energy is high, as Section 4 will show that savings of 46% are obtained by allowing this marginal quality degradation.

Choice of scaling factors

Scaling factors determine the target frame size decrease or increase for frames in a particular channel condition. The scaling applied determines as well the quality increase or degradation allowed for a particular frame. For our experiments the values in Table 2, showing good energy-quality tradeoff, were empirically obtained.

Table 2 Scaling factors applied

Channel	Factor	Channel	Factor
1~2	>1	5~6	0.7
3~4	0.9	7~8	0.6

The lower the scaling factor, the higher the frame quality degradation allowed. Nevertheless, the perceived quality degradation associated is partly dependent on the overall target bit rate. The higher the bit rate, the higher the encoding quality is and the impact of bit rate reduction becomes less noticeable. This way, for Foreman and target bit rates of 2 Mbps or 1 Mbps, no quality degradation is perceived. For lower target bit rates, such as 500 kbps the quality degradation can become more noticeable for aggressive scaling factors. The scaling factors that provide the best tradeoff in terms of energy and quality still need to be explored. Generally, its selection depends on the targeted encoding quality and on the occurrence probability of the CS.

Impact of non idealities

1. Mismatch of channel probabilities

The channel-adaptive RC is based on a priori knowledge of the CS probabilities. In practice, a slight mismatch occurs between the expected model probabilities and the probabilities observed in a shorter channel realization, which cannot reflect the global channel statistics. We observed that this mismatch does not impair the efficacy of the adaptive RC mechanism. The effect is that channel sequences with higher probability of bad CS allow higher energy savings while lower probability of bad CS decrease the potential savings.

2. Impact of feedback delay

The efficiency of any channel adaptation depends highly on both the speed at which the conditions are varying and the speed of the adaptation to these variations. The speed at which the channel conditions change is given by the coherence time of the channel, defined as the time, during which the channel remains unchanged. The RC mechanism only adapts at every video frame (33 ms at 30 fps). This requires the coherence time of the channel to be equal or longer to one video frame so that timely adaptation can be performed.

On the other hand, channel information needs to be accurate and received in time to allow correct adaptation. In practice, the information is fedback with a certain delay. If channel reciprocity is assumed, the CS can be computed at the transmitter with no incurred delay. If the CS is fedback from the receiver, the delay is piggybacked in the ACK and bounded by 3 ms due to the transmission at 6 Mbps of maximum data length (MTU) and ACK plus the SIFS (Short Inter Frame Space) (IEEE Std 802.11a, 1999). If feedback arrives when encoding of the current frame started, then the CS may be used for the next frame so a feedback delay of one video frame occurs. Delays of two or even a few video frames can occur only if more than one link is considered. In the next section we asses the impact of the delay on the adaptation efficiency. In current systems channel estimation is foreseen at the physical layer (IEEE Std 802.11a, 1999) incurring in marginal complexity.

Testbench

We use the MPEG-4 Simple Profile codec (de Vleeschouwer and Nilsson, 2001) and the video sequences Foreman (encoded at 500, 1000 and 2000 kbps) and Calendar and Mobile (at 2, 4 and 6 Mbps). Tests are run and averaged over several channel sequences.

RESULTS AND ANALYSIS

This section shows the results obtained for particular channel sequences as well as averaged results over different instantiations of channel sequences.

Fig.4 shows the normalized communication energy per frame (1 corresponds to 0.35 joules) for Foreman, normal RC in dashed, adaptive RC in solid line. It corresponds to the channel sequence in Fig.2. During bad channel conditions (between frames 100 to 150) the adaptive RC reduces the frame. This reduces the energy spent for transmission by at least a factor of 2 during bad channel conditions. Fig.5 shows the cumulative energy of Fig.4, normalized to the maximum (8 joules). For this case we can see how 46% of the communication energy can be saved, by using the adaptive RC (solid line). The results averaged over different channel sequences for Foreman at 1 Mbps are presented in the following tables. Averaged results for Mobile and different bit rates yield similar results.

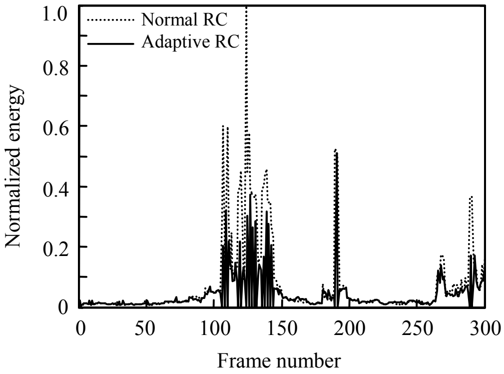

Fig.4 Adaptive RC decreases energy per frame

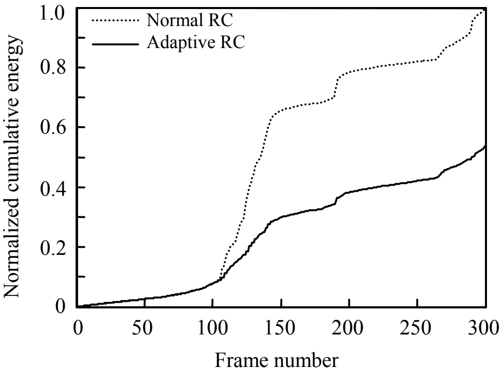

Fig.5 Cumulative energy

Table 3 shows average energy savings of 14% for Foreman at 1000 kbps with the adaptive RC without frame skipping. Feedback delays of 1 or 2 video frames (40 or 80 ms delay), can reduce energy savings of around 3% or 5%.

Table 3 Adaptive RC without frame skipping

Sequence	Energy (J)	Savings (%)	Average *PSNR* (dB)	Bitrate (kbps)
Normal RC	24.69	0.00	36.16	1000
Adaptive RC	21.22	14.07	36.05	995
1 frame delay	21.75	11.07	36.05	995
2 frames delay	22.34	8.91	36.05	995

The adaptive RC with frame skipping attains savings of 31% of the communication energy for Foreman and at least 30% for Mobile (Table 4). Around 1% or 2% of the frames are skipped, without degrading the perceptual visual quality and maintaining the average target bit rate. The effect of feedback delay on the performance is not dramatic (savings reduced between 5% and 8%), as most CS transitions occur between neighbor CSs.

Table 4 Adaptive RC with frame skipping

Sequence	Energy (J)	Saving (%)	Average *PSNR* (dB)	Frame rate	Bit rate (kbps)
Normal RC	24.69	0.00	36.16	25.0	1000
Adaptive RC	17.02	31.08	36.05	24.3	968
1 frame delay	18.26	25.82	36.05	24.3	968
2 frames delay	18.53	24.43	36.05	24.3	968

CONCLUSION AND FUTURE WORK

We have proposed a channel-adaptive RC mechanism that steers the instantaneous encoding rate according to the network conditions. The transmission power is optimized (saving of up to 30%) under quality constraints (barely 0.1 dB degradation). Moreover, the mechanism has low complexity and is suitable for real-time applications.

The adaptive RC not only reduces the communication energy but also allows investing more bits in error protection and correction, which in turn can increase the end video quality. It is interesting to extend the adaptive RC approach to the Advanced Video Codec (Wiegand, 2002), where frame size reduction can be performed by increasing of the QP and also by applying more complex coding tools. As these tools involve an increase of coding energy the tradeoff with the communication energy will need to be explored.

References

Chandramouli, R., Subbalakshmi, K.P., Ranganathan, N., 2004. Stochastic channel-adaptive rate control for wireless video transmission. *Journal on PRL*, **25**(7):793-806.

Chiang, T., Zhang, Y.Q., 1997. A new rate control scheme using quadratic rate distortion model. *IEEE Trans. Circuits Syst. Video Tech.*, **7**(1):246-250. [doi:10.1109/76.554439]

de Vleeschouwer, C., Nilsson, T., 2001. Motion Estimation for Low Power Video Devices. Proceeding of the IEEE ICIP01. Greece.

ETSI (European Telecommunications Standards Institute) 3ERI085B, 1998. Channel Models for HIPERLAN/2 in Different Indoor Scenarios.

Hsu, C.Y., Ortega, A., Khansari, M., 1999. Rate control for robust video transmission over burst-error wireless channels. *IEEE Journal on Selected Areas in Communications*, **17**(5):756-773. [doi:10.1109/49.768193]

IEEE Std 802.11a, 1999. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specs.

ISO/IEC JTC1/SC29/WG11, 2001. MPEG-4 Video Verification Model v18.0. Coding of Moving Pictures and Audio N3908. Pisa.

Krunz, M., Hassan, M., 2004. Adaptive Rate Control Scheme for Video Streaming over Wireless Channels. Proceeding of DCC'04.

Mangharam, R., Pollin, S., Bougard, B., Rajkumar, R., Catthoor, F., van der Perre, L., Moeman, I., 2005. Optimal Fixed and Scalable Energy Management for Wireless Networks. INFOCOM'05. USA.

Wiegand, T., 2002. Joint Video Team of ISO/IEC MP. Joint Final Committee Draft (JFCD) of Joint Video Specification (ITU-T Rec. H.264, ISO/IEC 14496-10 AVC).