Trade-offs between compression, energy and quality of video streaming applications in wireless networks

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***Abstract*—As throughput of wireless technologies had improved rapidly over the last decade, handheld devices became more attractive to the end users enabling multimedia applications "on-the-move". The uptime of mobile devices depends on their battery power that is not growing at the pace of communication technologies. In this study we describe the trade-offs between the power consumption, compression and the quality of video streaming in wireless environment. We show that using scalable [illegible] parameters may result in significant energy and bitrate savings at the expense of only slight degradation in quality, if at all. The amount of motion in a sequence plays a crucial role for energy savings when packet loss probability is non-negligible.**

I. Introduction

Over the last several years we have witnessed a tremendous growth of mobile market. It was stimulated by the increasing throughput of wireless access network nowadays reaching 100Mbps downlink for cellular systems and 500Mbps for local wireless access. Evolution of mobile computing over these years was on the pace with wireless technologies providing us with small handheld devices capable of storing large arrays of information and performing complex processing tasks. Coupled with the current state of networking media services these factors enabled penetration of these services to the air interface providing any available service anytime and anywhere.

One of the problems affecting the user experience of modern handheld devices is their limited uptime [3]. The reason is usage of advanced functional components such as high-definition displays, multi-core central and graphical processing units, complex modern wireless interfaces, etc. At the same time, over the last decade there were no significant breakthroughs in battery technologies [4], [5]. These batteries with slightly improved capacity are still used nowadays. Improving their capacity further is hardly feasible without significant increase of their size implying that conserving energy becomes critical problem.

In spite of old battery technology modern smartphones sometimes provide longer uptime in the stand-by regime compared to outdated mobiles. The reason is various energy conservation regimes used in devices. Once a smartphone is not used the display is turned off after some time, then, CPU goes to the sleeping mode. During the sleeping mode network interfaces are maintained at their minimum functionality. Various mechanisms of modern wireless systems are optimized with respect to power consumption. However, so far there were few studies trying to address the question of energy conservation when a handheld devices is in-use. Some of these studies are done in [2] and [1].

Video streaming is one of the most energy demanding application due to the usage of complex media encoding schemes. At the same time, modern wireless access technologies become more and more complicated involving sophisticated channel adaptation mechanisms and requiring more energy for communication. In this paper we explore and discuss interrelationship between the bitrate, perceived quality and total energy consumption of H.264/AVC-encoded video applications in wireless networks. Some previous studies on this subject can also be found in [6] and [7].

The paper is organized as follows. In Section II, we introduce objective quality metrics for video applications. Then, in Section III, we discuss parameters of H.264/AVC codec. Trade-offs and dependencies between bitrate, energy requirements, and perceived quality are analyzed in Section IV. Conclusions are given in the last section.

II. Perceived quality metrics

Some objective video quality assessment metrics were derived as extensions of the image quality assessment algorithms. The most popular video quality assessment metric based on this concept is PSNR. Given two vectors describing the original and distorted images $\vec{X} = \{x_i, i = 0, 1, \dots, N\}$, $\vec{Y} = \{y_i, i = 0, 1, \dots, N\}$ PSNR is

$$p = 10 \log_{10}\left(\frac{L^2}{m}\right), \; m = \frac{1}{N}\sum_{i=1}^{N}(x_i - y_i)^2, \qquad (1)$$

where L is the maximum possible pixel value of the image.

The main reason against using PSNR is that it was shown to have poor correlation with MOS grades in some cases. Although, some metrics were indeed shown to perform better than PSNR the research community still widely uses PSNR ad the main metric for perceived quality evaluation [8].

Another metric that is used in this work is the structural similarity index (SSIM) proposed in [9]. The SSIM index expresses the perceived quality by comparing local correlations in luminance, contrast, and structure between reference and distorted images. Given image vectors $\vec{X}$ and $\vec{Y}$, the following expression was proposed

$$s = \frac{2\mu_X\mu_Y + C_1}{\mu_X^2 + \mu_Y^2 + C_1} + \frac{2\sigma_X\sigma_Y + C_2}{\sigma_X^2 + \sigma_Y^2 + C_2} + \frac{2\sigma_{XY} + C_3}{\sigma_X\sigma_Y + C_3}, \quad (2)$$

where μ_X and μ_Y are sample means, σ_X and σ_Y are sample variances, σ_{XY} is sample cross-covariance between $\vec{X}$ and $\vec{Y}$. Constants C_1, C_2 and C_3 are used to stabilize SSIM when means and variances are exceptionally small. Performance of SSIM index was reported to be better than that of MSE/PSNR metric.

III. H.264/AVC CODEC

H.264 codec, standardized by ITU-T in cooperation with ISO/IEC, is also known as MPEG-4 Part 10, or, formally, ISO/IEC 14496-10. This standard is the latest generation of video codecs which is nowadays universally used in different applications ranging from storing to streaming [10], [11], [12]. To target various use cases it defines a number of profiles having different encoding complexities Special characteristics of H.264 pertaining to our study are described below.

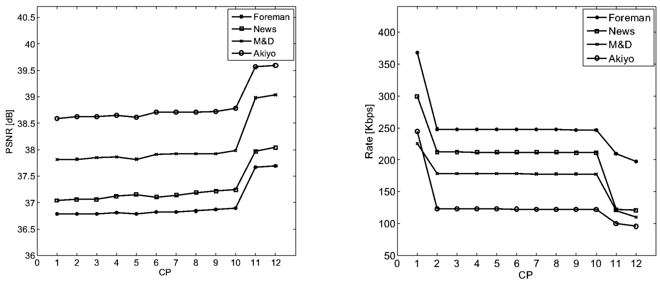
[illegible] and levels. Profiles are used to control the complexity and, thus, power consumption of the compression algorithm. Different profiles use different encoding techniques. In addition to the complexity and power consumption, another trade-off targeted in these profiles is quality enhancement and the complexity of decoder.

Levels make it possible to control the maximum data rate of the encoder and, in our context, can be used for controlling bitrate of networking video applications. Different levels also provide options to control the maximum resolution and solve memory issues which might happen at the decoder side.

2) The choice of input sequences: As the trade-offs between encoding parameters optimizing the bitrate, energy consumption and perceived quality can be quite complex it is important to wisely choose the input parameters for our experiments. Among all H.264 profiles, only SBP and SCBP can be used for video streaming.

The sequences we use, are "Akiyo", "Foreman", "Mother and daughter", and "News". "Akiyo" is the the one with the lowest motion condition. Background of this sequences is a still image and with only the head of the newsman moving. In "Mother and daughter" sequence, although the background is always still, both mother and daughter slightly move and it is classified as a the one with moderate motion. "News" sequence has a moving background but the size of the moving part is just a small portion of the whole scene. This sequence is a medium motion one. Finally, "Foreman" sequence has a high motion conditions.

3) Complexity and quantization parameters: To analyze the effect of encoding parameters on the data rate, complexity, and power consumption in the context of video sequences, two additional issues must be addressed. Firstly, the parameters must be chosen in a way that encoding and decoding processes



(a) PSNR (b) Bitrate

Fig. 1. Bitrates and PSNR values for considered CPs (QP=28).

as well as the bitrate are suitable for real-time applications. Complexity of encoding algorithm is another issue which should be chosen such that processors of portable devices are able to handle it. The associated power consumption must be acceptable for batteries of these devices. These requirements [illegible]

SBP profile of H.264 standard is divided into twelve different complexity levels. Following [13] we refer to these levels as complexity parameters (CP), i.e. CP1, CP2, etc. The difference between them is in the searching techniques they use, prediction schemes and other factors that directly affect the complexity of the encoder. Thus, for a given video sequence each CP corresponds to a certain amount of processing power required for compression. Choosing different CPs should also change the response of the compressed bitstream to the packet losses. However, CPs from 2 to 10 within a single profile do not affect the perceived quality after compression. Fig. 1(a) shows PSNR for all chosen sequences. We see that PSNR increases by no more than 1dB as we go from CP2 to CP10. Although the value of CP is expected to affect the bitrate, it has been demonstrated in [13] and [14] that its effect is not noticeable. As shown in Fig. 1(b), the bitrate for the CP values ranging from 2 to 10 changes by at most 1Kbps.

To be able to modify the perceived quality after compression and the resulting rate of the bitstream we take advantage of different quantization steps often called quantization parameters (QP). QP determines how much spatial details are taken into account in the encoding process. Thus, after choosing the CP value specifying encoding parameters for motion compensation, one can use QP to provide different quality levels. It is important to note that changing QP values within a single CP does not drastically affect the operating frequency of a CPU clock implying that the energy required for compression remains almost intact.

IV. TRADE-OFFS AND DEPENDENCIES

A. Bitrate

Fig. 2 shows the bitrate as a function of QP. Observe that the bitrate of the sequences decreases as QP increases and this dependence is non-linear. Secondly, we see that the bitrate is a function of the amount of motion in a sequence.

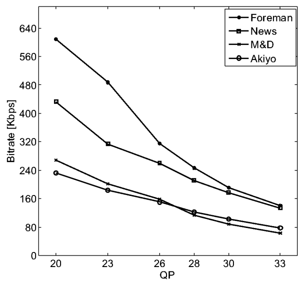
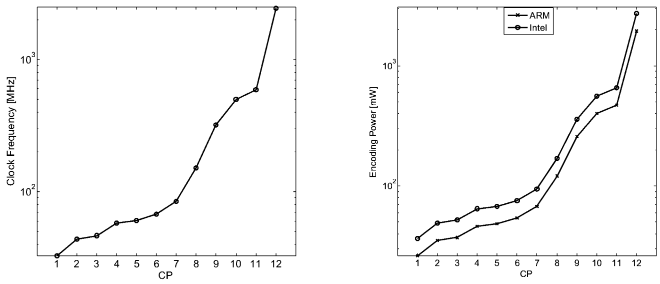


Fig. 2. Bitrate of sequences for different values of QP.



(a) Clock frequency (b) Encoding power

Fig. 3. Clock frequency and encoding power for different CPs.

B. Power consumption

1) Encoding power: We determine the amount of encoding energy required for each CP using the two-step procedure. First, we perform the mapping between CPs and the required clock frequency. Then, using these frequencies, we calculate the encoding power consumption for different processors. We are extending the work done in [15] by including the effect of rate on transmission power.

Fig. 3(a) shows the mapping between different CPs and corresponding clock frequencies measured in MHz. As one may observe, there is a monotonic non-linear increase in the clock frequency as the value of CP increases. The dependence is almost exponential starting from CP6 implying that the increase in loss persistency should be comparable for high value of CP to be useful.

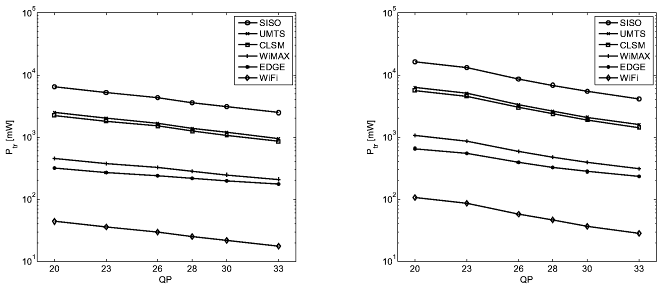
The clock frequency is a processor-independent metric [16]. To calculate the actual encoding power consumption, we need to specify a processor of interest. In this study, two newly released processors, used in modern smartphones and are investigated. These are Intel Atom with x86-64 instruction set and ARM Cortex-A9 with instruction set ARMv7. According to [17] Intel dual-core processor consumes 1.12mW per MHz while ARM Cortex-A9 is more energy efficient consuming 0.8mW per MHz. Knowing the amount of energy consumed per cycle per second and those data provided in Fig. 3(a) we calculate the encoding power consumption for different CPs for both processors.

Fig. 3(b) shows the encoding power consumption for different CPs. As we expected, Intel Atom x86-64 consumes more energy than ARM Cortex-A9 and the difference becomes more noticeable for large values of CP associated with more complex motion compensation algorithm, i.e. the absolute difference between Intel Atom x86-64 and ARM Cortex-A9 is just 12mW for CP1 and as large as 160mW for CP9. Further, these dependencies are qualitatively similar for both processors. The difference in power consumption is close to linear for both processors as we go from CP1 to CP5. In absolute numbers CP5 consumes just 25% more power compared to CP1 for ARM Cortex-A9 and 50% more power for Intel Atom x86-64. Further, this dependence grows exponentially fast. Finally, the dependence again become linear for CP7-CP9. Such a complex linear-exponential-linear dependence as well as difference in absolute numbers between CP1 and CP9 allows us to assume that these high values of CP are useful only if they associated with similar increase in resistance to packet losses.

2) Transmission power: The only factor affecting the transmission power is QP. As we already shown in Fig. 2 increasing the value of QP reduces the compressed data rate resulting in smaller amount of energy required for transmission. It is also evident that the amount of the motion in the video affects the compressed data rate. Thus, the transmission energy depends on the type of the sequence as well.

To see the effect of QP and the amount of motion on the required transmission power we consider the latter parameters as a function of two different video sequences (”Foreman” and ”Akiyo”) and six values of QPs: 20, 23, 26, 28, 30, and 33, see Fig. 4. As we expected, setting QP to 20 results in the highest amount of energy required for transmission while letting QP be 33 requires the least amount of energy. The ultimate reason relates back to the bitrate required for different QPs, see Fig. 2. Further, the amount of energy required for transmission varies in a great range. It is important to highlight that the range of transmission power consumption greatly differs for a single sequence, i.e. this range is approximately 6.5W for the ”Akiyo” and as high as almost 16W for ”Foreman”. Further, the transmission power consumption scales exponentially (linearly in log scales). Taking into account that QP directly affect quality of video after compression the corresponding increase in PSNR should also be of exponential nature to warrant the use of small values of QP. Finally, observe that for both considered sequences the difference between QP20 and QP23 is not as high as the difference between between Q23 and Q26, say, implying that the transmission energy consumption decreases slightly faster as we go from small QP values to big ones.

Recall, that QP value does not affect the amount of energy spent for encoding, while CP values in the range $1-10$ do not affect the amount of energy required for transmission nor the perceived quality after compression (see Fig. 1(a)). An important consequence which can be deduced analyzing the data presented in Fig. 4 and Fig. 3(b) is that the energy required for transmission in cellular technologies is comparable (of the same magnitude) to that required for encoding



(a) Akiyo (b) Foreman

Fig. 4. Transmission power for different values of QP.

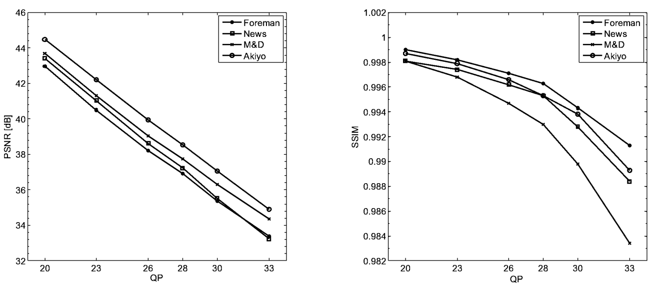
for all considered values of QP. This gives us potential for trading-off encoding power consumption in favor of the transmission one and vice versa. Particularly, depending on the type of transmission technology and a chosen value of CP there indeed could be a trade-off between the amount of energy spent for communication and for encoding. For a given technology this value is different. Particularly, for Wi-Fi and "Foreman" sequence all encoding schemes with CP values up to 7 consume less encoding energy than that required for transmission for any considered values of QP. When CP increases further the encoding power becomes the dominant source of power consumption. For low motion "Akiyo" sequence almost all CP values results in domination of encoding power component in the total energy consumption. For Worldwide Interoperability for Microwave Access (WiMax) and "Foreman" sequence the only the CP value resulting in more compression energy consumption is 12 while for "Akiyo" the encoding energy component prevails starting from CP 9. For the rest of considered technologies the amount of energy required for communication is greater than the maximum possible compression energy corresponding to CP 12 for both "Foreman" and "Akiyo" sequences. However, notice that the for UMTS and LTE CLSM technologies the amount of power required for transmission is only slightly more than that required for compression. Taking into account ever decreasing size of cells in cellular systems as well as those efforts devoted to energy efficient communications one may expect that both energy sources will be comparable in future cellular systems.

C. Perceived quality

In this subsection we evaluate the perceived quality using PSNR and SSIM metrics at the following two logical points: (i) after encoding, to evaluate the impact of compression impairments introduced by different values of QP and (ii) after transmission, to capture the joint effect of compression and lossy transmission medium.

1) Perceived quality after compression: Lossy compression is one of the two major reasons for quality degradation of a video. To evaluate the perceived quality after compression for a wide range of parameters we encoded original YUV video sequences and then estimated PSNR and SSIM at the output of the codec. For encoding and decoding purposes a reference H.264/AVC software JM v.15 has been used [18]. In all encoding procedures the frame per second (fps) parameter was set to 30.

Fig. 5 provides the values of PSNR and SSIM as a function of QP. Recall from Fig. 2 that this trend is accompanied by the decrease in the bitrate. For PSNR the decrease is almost linear across all considered values of QP while SSIM decreases at way lower rate especially for small-to-medium values of QP. Comparing relative gains in bitrate and perceived quality one may notice that the perceived quality decreases at the slower pace compared to the bitrate as QP increases and this dependence is qualitatively similar for sequences having different amount of motion. This is an important observation for the process of joint energy/quality/rate optimization. Indeed, switching from QP20 to QP26 for "Foreman" sequence we are loosing just around 4dB in PSNR while saving approximately 30% in the bitrate and around 60% in transmission power. While for high motion sequence these gains can be slightly less the associated decrease in PSNR is less as well. Observe that additional energy saving are also possible as all CP values in the range 2-10 is characterized by the same quality after compression implying that there is not need to use the highest possible CP for encoding.



(a) PSNR (b) SSIM

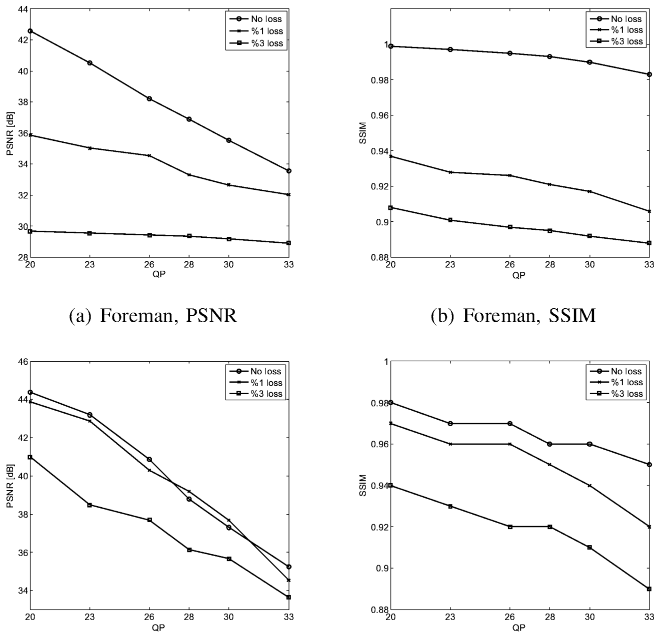
Fig. 5. PSNR and SSIM for different values of QP.

2) Perceived quality after transmission: A transmission medium is the second source of quality degradation. Here, we investigate the effect of packet losses on the perceived quality by artificially introducing packet losses into the stream of packets. Here, we show illustrations for "Foreman" only as the rest of considered sequences show qualitatively similar behavior.

The experiments were performed as follows. First, we encoded the YUV sequence in RTP mode using JM v.15 implementation of H.264 codec. Let N denote the number of RTP packets obtained. To emulate the effect of lossy transmission medium a sequence of 0 and 1 of length $N-3$ is then generated, where 0 denotes a received packet, while 1 corresponds to the lost one. Packet losses were assumed to happen independently with a certain packet loss ratio (PLR) implying that there is no grouping of losses. This sequence was further applied to the packetized RTP sequence starting from the fourth packet by dropping and keeping packets. We explicitly assumed that the first three packets of a sequence are received correctly. The reason is that these packets carry information related to the choice of the decoding procedure and loosing at least one of them would fail the decoding process completely. Although for the tested sequences it is rather significant portion of the content, in real-life applications this just an small part of the stream. Finally, after encoding and dropping of RTP packets, we decode the compressed bitstream.

There are a number of issues one have to deal with performing such experiments. As we already saw, changing QP values produces different compressed bitrates. Since the RTP packet size depends on the amount of information produced by a codec per frame generation interval (1/30s.) loss of a single packet would affect different amount of compressed data for different QPs. One way around this problem is to measure the loss rate not in packets but in some rather small reference units, e.g. bytes. However, we assumed that the loss unit is a packet implying that the same PLR leads to different amount of impairments. Further, it is also possible to add the effect of grouping of packet losses by introducing dependency into sequence of 0s and 1s. For, example, discrete autoregressive process of order one, DAR(1), provide an easy way to generate binary sequences having some predefined lag-1 autocorrelation and PLR in a sequential manner. The selection of the loss concealment algorithm is another issue that has to be addressed. Most real life implementations do not use advanced error concealment schemes relying solely on replacing the lost frame with the previous one that has been decoded correctly (frame copy). Motion copy is another simple way to replace regions of a frame contained in the lost packet. There are also techniques based on interpolation recovering lost macro block information, e.g. outer boundary matching (OBM), zero motion vector (ZMV), average motion vector (AMV) algorithms, see also [19], [20]. These advanced algorithms bring additional complexity that is often avoided in handheld devices.

Both QP and CP are expected to affect the perceived quality after transmission. In particular, increasing the value of QP we decrease the amount of information in each packet implying that the same PLR would lead to different impairments. Making the value of CP higher we use more sophisticated compression algorithms theoretically improving resistivity of the bitstream to packet losses. Consider the effect of QP first. Fig. 6 provides PSNR values for ”Akiyo” and ”Foreman” sequences, considered values of QP and three different packet loss conditions (0%, 1% and 3% PLR). The general trend is similar to what we expected, that is, both metrics decrease when PLR increases. One important observation is that increasing the value of QP for high motion sequence the same amount of losses leads to smaller impairments. Considering ”Foreman” sequence for 1% PLR PSNR changes by 3dB, while for 3% PLR the change is just 2dB. At the same time in loss-free environment the difference between QP20 and QP33 as large as 9dB. However, for low motion sequence like ”Akiyo” these conclusions do not hold.



(a) Foreman, PSNR (b) Foreman, SSIM

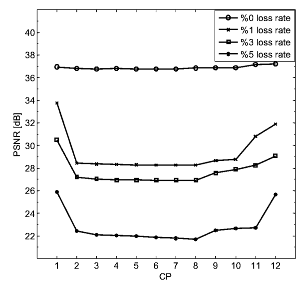
(c) Akiyo, PSNR (d) Akiyo, SSIM

Fig. 6. PSNR and SSIM for different sequences and values of QP.

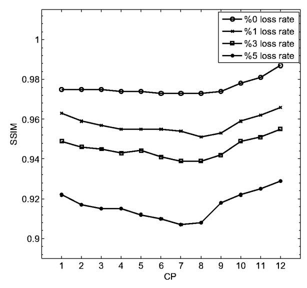
Consider now the effect of CP on the perceived quality provided after transmission. Fig. 7 illustrates PSNR and SSIM for ”Foreman” and ”Akiyo” sequences, several CP values and few values of PLR. For all CPs values the QP value was kept at 28. Recall, that decreasing the value of CP we simplify the compression algorithm making the bitstream (theoretically) more sensitive to packet loss impairments. However, at the same time we significantly reduce power consumption required for encoding. Also recall that all values of CP between 2 and 10 results in the same rate and perceived quality after encoding. That is, the only reason for changing CP is to get better loss protection. Analyzing data provided in Fig. 7 we see that the quality response to packet losses remain the same for CP values in the range 2-10, i.e. the difference is less than 1dB. Hence, we see that the choice of CP does not affect the perceived quality after transmission for CP values of SBP profile suitable for video streaming. All these imply that there is no need to use more complex encoding procedure resulting in extreme energy consumption, see Fig. 3.

V. Conclusions

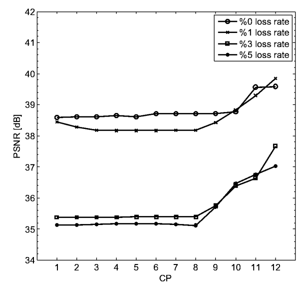
We examined trade-offs between perceived quality, bitrate and energy consumption for video streaming applications in wireless environment. We concentrated on the time period when a video application is ”on” and explored the way how decrease the amount of energy required for running such a service while maintaining the best possible quality. We considered only those parameters of H.264 codec suitable for ”on-the-fly” encoding at mobile devices, i.e. SBP profile, CP



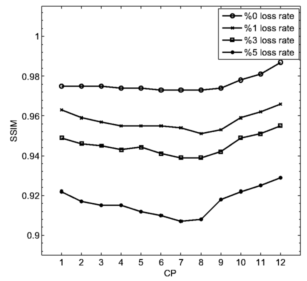
(a) Foreman, PSNR



(b) Foreman, SSIM



(c) Akiyo, PSNR



(d) Akiyo, SSIM

Fig. 7. PSNR and SSIM for different sequences and values of CP.

in the range 2-10, QP in the range 20-33.

In lossy environment (non-negligible PLR) both CP and QP do not drastically affect the perceived quality of video information for high-motion sequences. Since CP value also does not affect the amount of power required for communication one may use CP1 resulting in the least possible encoding complexity and power consumption required for encoding. The difference between CP1 and CP10 is approximately 500% (0.5W for Intel Atom with x86-64 and 0.45W for ARM Cortex-A9). Further, choosing higher values of QP would significantly reduce the bitrate required from the network and power required for transmission. The gain in power when changing from QP20 to QP33 is 20mW for IEEE 802.11, 40mW for IEEE 802.16, 150mW for UMTS and LTE CLSM, and 400mW for LTE SISO.

For loss-free environment or when PLR is smaller than 0.1% the involved trade-offs are more complicated. Firstly, as before, the value of CP for a considered profile does not produce any substantial effect on the perceived quality and bitrate implying that choosing CP1 we minimize the amount of energy required for encoding. However, the choice of QP affects the resulting quality substantially. However, even in this case there is potential for saving energy and reducing bitrate requirements. In this work, we have performed our experiments on YUV sequences. For the future work, designing a testbed for power [illegible] samples, and finally, coming up with an integraded system could be considered.

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