ENERGY-EFFICIENT WIRELESS VIDEO CODING AND DELIVERY

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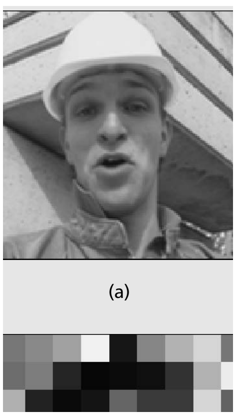

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ABSTRACT

Transmitting video over wireless channels from mobile devices has gained increased popularity in a wide range of applications. A major obstacle in these types of applications is the limited energy supply in mobile device batteries. For this reason, efficiently utilizing energy is a critical issue in designing wireless video communication systems. This article highlights recent advances in joint source coding and optimal energy allocation. We present a general framework that takes into account multiple factors, including source coding, channel resource allocation, and error concealment, for the design of energy-efficient wireless video communication systems. This framework can take various forms and be applied to achieve the optimal trade-off between energy consumption and video delivery quality during wireless video transmission.

INTRODUCTION

In an increasing number of applications, video is transmitted to and from portable wireless devices such as cellular phones, laptop computers connected to wireless local area networks (WLANs), and cameras in surveillance and environmental tracking systems. For example, the dramatic increase in bandwidth brought by new technologies, such as the present third-generation (3G) and emerging fourth-generation (4G) wireless systems, and the IEEE 802.11 WLAN standards, is beginning to enable video streaming capability in personal communications. Although wireless video communications is highly desirable in many applications, a major limitation in any wireless system is the fact that mobile devices typically depend on a battery with a limited energy supply. Such a limitation is especially a concern because of the high energy consumption rate in encoding and transmitting video bitstreams. Thus, efficient use of energy becomes highly important, and sometimes the most critical part in the deployment of wireless video applications.

To design an energy-efficient communications system, the first issue is to understand how energy is consumed in mobile devices. Generally speaking, energy in mobile devices is mainly used for computation, transmission, display, and driving speakers. Among those, computation and transmission are the two largest energy consumers. During computation, energy is used to run the operating system software, and encode and decode the audio and video signals. During transmission, energy is used to transmit and receive the radio frequency (RF) audio and video signals. It should be acknowledged that computation has always been a critical concern in wireless communications. For example, energy-aware operating systems have been studied to efficiently manage energy consumption by adapting the system behavior and workload based on the available energy, job priority, and constraints. Computational energy consumption is especially a concern for video transmission, because motion estimation and compensation, forward and inverse discrete cosine transforms (DCTs), quantization, and other components in a video encoder all require a significant number of calculations. Energy consumption in computation was recently addressed in [1], where a power rate distortion model is proposed to study the optimal trade-off between computation power, transmission rate, and video distortion. Nonetheless, advances in very large-scale integration (VLSI) design and integrated circuit (IC) manufacturing technologies have led to ICs with higher and higher integration densities using less and less power. According to Moore's Law, the number of transistors on an IC doubles every 1.5 yr. As a consequence, the energy consumed in computation is expected to become a less significant fraction of the total energy consumption. Therefore, in this article we concentrate primarily on transmission energy, focusing on the problem of how to encode a video source and send it to the base station in an *energy-efficient way*, as shown in Fig. 1. The goal is to minimize the amount of distortion at the receiver given a limited amount of transmission energy, or vice versa, to minimize the energy consumption while achieving a targeted video delivery quality.

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One difference between video transmission and more traditional data communications is that video packets are of different importance. In order to efficiently utilize energy, unequal error protection (UEP) is usually preferred (e.g., it is more efficient to use more power to provide more protection when transmitting the more important packets). This requires a "cross-layer" perspective [2] where the source and network layers are jointly considered. Specifically, the lower layers in a protocol stack, which directly control transmitter power, need to obtain knowledge of the importance level of each video packet from the video encoder, which is located at the application layer. On the other hand, it can also be beneficial if the source encoder is aware of the estimated channel state information (CSI) passed from the lower layers and which channel parameters at the lower layers can be controlled, so it can make smart decisions when selecting the source coding parameters to achieve the best video delivery quality. For this reason, joint consideration of video encoding and power control is a natural way to achieve the highest efficiency in transmission energy consumption.

In this article we present a general framework for the joint consideration of source coding and transmission energy consumption in a wireless video transmission system. The allocation of energy affects the quality or level of distortion of the received video sequence, as well as the required delay before the sequence may be displayed. In addition, it affects the level of interference in a multiple-user environment. In this framework we discuss research efforts focused on balancing energy efficiency with the above considerations.

The framework presented here is general in the sense that it can be used in a variety of different applications and network settings. Our focus is on point-to-point or unicast communications, although some of these ideas also apply to multicast scenarios. In addition to these approaches, there has been significant research on new video coding paradigms and network protocols for multimedia communications. Those approaches may provide additional directions that can be incorporated into this framework.

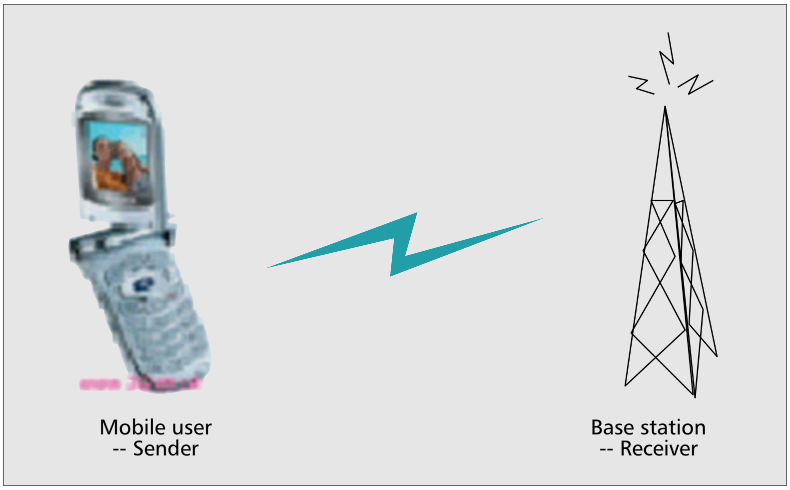

Figure 1. *Video transmission from a mobile user to a base station.*

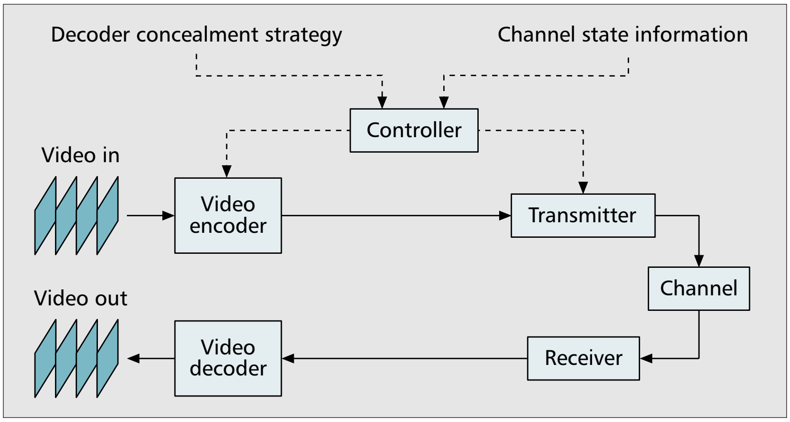

Figure 2. *Block diagram of wireless video communication systems.*

Wireless Video Communication Systems

We begin by providing a high-level overview of a wireless video transmission system, followed by our general problem formulation.

Wireless Video Communication System

Figure 2 highlights some of the major conceptual components in a wireless video communication system. At the sender side, video packets are first generated by a video encoder, which performs compression by exploiting both temporal and spatial redundancy. After passing through the network protocol stack (e.g., RTP/UDP/IP), transport packets are generated and then transmitted over a wireless channel that is lossy in nature. Therefore, the video sequence must be encoded in an error-resilient way that minimizes the effects of losses on the decoded video quality. Let S denote the set of *source coding parameters* that directly control video delivery quality (e.g., prediction mode and quantization stepsize).

In order to combat channel errors, forward error correction (FEC) may be applied at the lower layers such as the link and physical layers. In addition, at the physical layer, modulation modes and transmitter power may be able to be adjusted according to the changing channel conditions. Scheduling the transmission of each packet may also be an adaptable parameter. In Fig. 2, the functionality of these lower layer adaptations is indicated by the "transmitter" block. Let C represent the set of *channel parameters* that can be controlled at the transmitter.

At the receiver, the demodulated bitstream is processed by the channel decoder, which performs error detection and/or correction. This functionality is represented by the "receiver" block in Fig. 2. Corrupt packets are usually discarded by the receiver, and are therefore considered lost. In addition, packets that arrive at the receiver beyond their display deadlines are also treated as lost. This strict delay constraint is another important difference between video communications and many other data transmission applications. The video decoder then decompresses video packets and displays the resulting video frames in real-time (i.e., the

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video is displayed continuously without interruption). The video decoder typically employs concealment techniques to mitigate the effects of packet loss.

Recall that our goal is to achieve the best video delivery while using a minimum amount of transmission energy. Wireless channels typically exhibit high variability in throughput, delay, and packet loss. Providing acceptable video quality in such an environment is a demanding task for the video encoder and decoder, as well as the communication and networking infrastructure. In each of these components, a number of coding and transmission parameters may be adapted based on source content and available CSI. In addition, factors affecting transmission energy consumption include the power used for transmitting each bit, the modulation mode, and channel coding rate at the link layer or physical layer. In order to save energy, those parameters should also be adapted to the video content and the CSI. The controller block in Fig. 2 indicates the component of the video transmission system responsible for adapting the source coding parameters, S, and the channel parameters, C, based on knowledge of the concealment strategy, the source content and any available CSI. As noted in the introduction, we focus on cases where these parameters are jointly adapted in a cross-layer framework.

General Problem Formulation

We consider techniques that efficiently adapt the source parameters, S, and channel parameters, C, in order to minimize the end-to-end distortion while meeting the energy and delay constraints. This problem can be formally stated as

$$\min_{\{S,C\}} D_{tot}(S,C); \text{ subject to}: E_{tot}(S,C) \le E_0 \text{ and } T_{tot}(S,C) \le T_0, \quad (1)$$

where E_0 is the maximum allowable energy consumption, and T_0 is the end-to-end delay constraint imposed by the application. For streaming applications, the delay constraint can be modeled by taking into account the dynamics of the encoder buffer and the playback buffer at the receiver [3].

The selection of S and C affects the end-to-end distortion D_{tot}, the end-to-end delay T_{tot}, and the total energy E_{tot} for delivering the video sequence to the receiver. We use $D_{tot}(S,C)$, $E_{tot}(S,C)$, and $T_{tot}(S,C)$ to explicitly indicate these dependencies. Distortion is caused by both source coding artifacts and channel errors, and is discussed in greater detail. The energy consumption E_{tot} is caused by a variety of channel parameters, and is discussed further. The end-to-end delay T_{tot} is the time between when a video frame is captured at the transmitter and when it is displayed at the receiver. T_{tot} depends in part on the number of bits used to encode the sequence, the transmission rate, and any scheduling decisions made by the transmitter.

To solve the problem in Eq. 1, we need to characterize how each adaptation component affects the video delivery quality and transmission energy. We discuss this in detail later.

Source Coding Adaptation

For video coding, the mean squared error (MSE) and peak signal-to-noise ratio (PSNR) are widely used in evaluating reconstruction quality, where PSNR in dB is defined as $10\log(255^2/\text{MSE})$. For video delivery over a lossy channel, the distortion at the receiver is a random variable from the sender's point of view. Thus, the expected end-to-end distortion (averaged over the probability of loss) is usually used to characterize the received video quality, and guide the source coding and transmission strategies at the sender. The expected distortion for the kth packet can be written as

$$E[D_k] = (1 - \rho_k)\, E[D_{R,k}] + (\rho_k)\, E[D_{L,k}], \quad (2)$$

where ρ_k is the probability of loss for the kth packet, $E[D_{R,k}]$ is the expected distortion if the packet is *received* correctly, and $E[D_{L,k}]$ is the expected distortion if the packet is *lost.* $E[D_{R,k}]$ accounts for the distortion due to source coding as well as error propagation caused by interframe coding. $E[D_{L,k}]$ accounts for the distortion due to concealment. The probability of packet loss depends on the CSI, transmitter power, and channel coding used, and is addressed later.

In addition to the expected value of the distortion, Eq. 2, the variance in distortion caused by random channel errors directly impacts the received video quality. In order to limit large variations in quality between different channel loss realizations, a novel approach called *variance-aware per-pixel optimal resource allocation* (VAPOR) has recently been proposed [4]. This approach aims to improve the reliability of video transmission systems by making it more likely that what the receiver sees closely resembles the mean end-to-end distortion calculated at the transmitter. Next, we discuss error-resilient source coding and error concealment.

Error-Resilient Video Coding

Here we focus on one of the most widely utilized video coding techniques, block-based motion compensated (BMC) video coding (e.g., as applied in H.263 and MPEG-4). With this approach, each frame is divided into macroblocks (MBs) that can be either independently encoded (intracoded) or predictively coded from a reference MB in a previous frame (intercoded). For intercoding, a motion vector describes where the reference MB is located in the reference frame. Temporal prediction offers increased coding efficiency over intracoding, but is susceptible to error propagation. Transform coding, followed by quantization and entropy coding, completes the BMC coding process.

Error-resilient source coding refers to techniques that add redundancy at the source coding level to prevent error propagation and limit the distortion caused by packet losses. Such techniques are usually composed of resynchronization marking, data partitioning, and reversible variable-length coding (RVLC) for wireless video. In packet-switched networks, they may include prediction mode selection, scalable coding, and multiple description coding (MDC). In addition, packet dependency control has been recognized as a powerful tool to increase error robustness. Common methods for packet dependency control are long-term memory (LTM) prediction for MBs, reference picture selection (RPS), intra-MB insertion, and video redundancy coding (VRC) [4].

All the above-mentioned components can be viewed as source coding parameters, S, in Eq. 1. The selection of S affects the source bit rate (i.e. the transmission delay) as well as the term $E[D_{R,k}]$, in Eq. 2. Our focus is on BMC video coding; furthermore, our attention is on packetized video transmission. More specifically, the source coding parameters considered here are the prediction mode (intra or inter) and the quantization step-size for each MB or packet.

Error Concealment

Error concealment refers to post-processing techniques employed by the decoder to conceal lost information by exploiting the spatial and temporal redundancy in the received video sequence. These methods can be broadly classified into spatial and temporal domain approaches. With spatial approaches, missing data is reconstructed using neighboring spatial information, whereas with temporal approaches, lost pixels in the current frame are reconstructed from received or concealed pixels in the previous frame. More complex concealment strategies may use both temporal and spatial information [5]. The error concealment strategy used is directly related to the calculation of $E[D_{L,k}]$. Therefore, the sender needs to know the error concealment strategy used by the receiver.

We emphasize that although error concealment may not appear to be directly related to any source coding parameter and channel parameter, it has significant impact on the selection of those parameters. For example, based on a given error concealment strategy, if we know that a certain packet is easily concealable at the receiver once it is lost, we may want to simply not transmit this packet, and use the saved bits and energy for other packets that are difficult to conceal once they are lost (we referred to this technique as *generalized* skip in [6]).

Channel Adaptation

In this section we discuss the channel parameters that can be manipulated for each video packet in detail. We also discuss models to illustrate how these parameters affect the properties of the communication channel as seen by the video encoder, and thus determine the video delivery quality and transmission energy.

Transmission Energy

The energy needed to send a packet of L bits with transmission power P is given by $E = PL/R$, where R is the transmission rate in source bits per second. These three quantities can be adapted in a variety of ways in an actual system. For example, power adaptation can be implemented by power control at the physical layer. The change of the transmission rate R can be implemented by selecting different modulation modes or channel rates, or allowing a waiting time for each packet before transmission. In addition, it can be implemented by selecting different rate channel codes at the link or physical layers (e.g., as in an IEEE 802.11 system). Next, we discuss channel models to show how these factors are related to the quality of the delivered video.

Channel Models

In wireless systems, one channel parameter that can be specified is the transmission power used to send each packet. For a fixed transmission rate, increasing the transmission power will increase the received signal-to-noise ratio (SNR) and result in a smaller probability of packet loss. This can be modeled by letting the packet loss probability of the k-th packet be given by

$$\rho_k = f(P_k, \theta_k), \quad (3)$$

where P_k is the transmission power used for the packet, and θ_k represents the available channel state information (e.g., the fading level and average noise power). In many systems the transmitter is able to estimate the channel state (e.g., using a pilot signal or feedback from the receiver). The specific channel state information needed to relate the effect of resource adaptation on the probability of packet loss depends on which channel model is used. The function f could be determined empirically or modeled analytically. For example, in [6] an analytical model based on the notion of outage capacity [7] is used. In this model a packet is lost whenever the fading realization results in a channel with a capacity less than the transmission rate. Another potential way to determine f is to use bounds for the bit error rate (BER) for a given modulation and coding scheme; for example, in [8] a model based on the error probability for binary phase shift keying (BPSK) in a Rayleigh fading channel is used.

In addition to transmission power, a second channel parameter is the transmission rate. A variety of rate adaptation techniques such as variable rate spreading and adaptive modulation and coding [9] may be used. In modern wireless systems, including 3G cellular systems, these parameters can be adapted on a fast timescale (on the order of 10 ms). The probability of packet loss for one packet can be written as

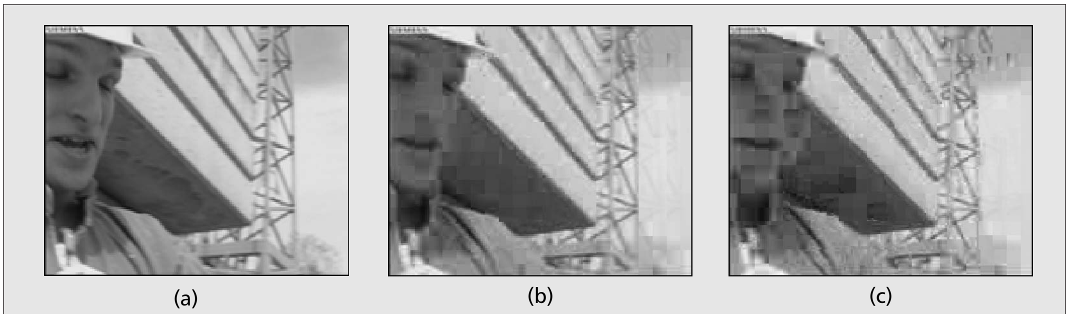
$$\rho_k = f(P_k, R_k, \theta_k), \quad (4)$$

where R_k denotes the transmission rate assigned to the kth packet. For example, in [8] a model was considered where the transmission rate was adapted by changing the amount of FEC applied to each packet using a rate-compatible convolution code (RCPC).

In an energy-efficient wireless video transmission system, transmission power needs to be balanced against delay to achieve the best video quality. For example, for a fixed transmission power, increasing the transmission rate will increase the BER but decrease the transmission delay needed for a given amount of data (or allow more data to be sent within a given time-period). Furthermore, the amount of transmission energy required to achieve a certain level of distortion typically decreases with increased delay. For example, in a wireless system, the transmission energy required to maintain a fixed probability of error can be reduced by increasing the transmission time and decreasing the trans-

We emphasize that although error concealment may not appear to be directly related to any source coding parameter and channel parameter, it has significant impact on the selection of those parameters.

In order to maintain a certain probability of loss, the energy consumption increases as the transmission rate increases. Therefore, in order to reduce energy consumption, it is advantageous to transmit at the lowest rate possible.



■ **Figure 3**. *Frame 92 in the "Foreman" sequence: a) original frame; b) expected frame at the decoder using the JSCPA approach; c) expected frame at the decoder using the ISCPA approach.*

mission power [10]. This observation is used in [11] to provide energy efficient packet transmission over wireless links. Therefore, in order to efficiently utilize resources such as energy and bandwidth, those two adaptation components should be jointly designed.

ENERGY-EFFICIENT VIDEO CODING AND TRANSMISSION

In this section we use several examples to show how the source coding and channel parameters can be jointly selected to achieve energy-efficient video coding and transmission.

JOINT SOURCE CODING AND POWER ADAPTATION

Joint source coding and power allocation techniques deal with the varying error sensitivity of video packets by adapting the transmission power per packet based on the source content and the CSI. In other words, these techniques use transmission power as part of a UEP mechanism. In this case, the channel coding parameter is the power level for each video packet. Video transmission over code-division multiple access (CDMA) networks using a scalable source coder (3-D SPIHT) along with error control and power allocation is considered in [12]. A scheme for allocating source rate and transmission power under bandwidth constraints is considered in [13]. In [6] optimal mode and quantizer selection are considered jointly with transmission power allocation.

To illustrate some advantages of joint adaptation of the source coding and transmission parameters in wireless video transmission systems, we present some experimental results, which are discussed in detail in [6]. We compare a joint source coding and transmission power allocation (JSCPA) approach with an independent source coding and power allocation (ISCPA) approach in which S and C are independently adapted. Figure 3 shows an expected reconstructed frame from the "Foreman" sequence when the same amount of energy is consumed in the two approaches. Clearly, the JSCPA approach achieves much better delivery quality than the ISCPA approach.

Figures 4a and 4b show frames 42 and 43 of the "Foreman" sequence, respectively. For frame 43, the two approaches can achieve the same expected video quality, but the JSCPA approach needs nearly 60 percent less energy to transmit this frame than the ISCPA approach. Figures 4c and 4d show the probability of loss for each packet in frame 43 for the JSCPA and ISCPA approach, respectively. Darker MBs correspond to a smaller probability of packet loss; MBs that are not transmitted are marked by white. As seen in Fig. 4c, more protection is given to the region of the frame that corresponds to the foreman's head. Therefore, more power is used to transmit this region as opposed to the background. As shown in Fig. 4d, however, the ISCPA approach has fixed probability of loss, which means that the power used to transmit the region corresponding to the foreman's head is the same as the power used to transmit the background. Therefore, the ISCPA approach wastes energy by transmitting MBs in the background with the same power as MBs in the high activity region.

As for the source coding, in the ISCPA approach the video encoder may allocate more bits to packets in high activity regions, as shown in Fig. 4f. Because the transmission power is fixed in this approach, more energy is used to transmit packets with more bits, as shown in Fig. 4h. Therefore, in the ISCPA approach, more energy may be allocated to high activity regions, but the likelihood of these regions being correctly received is the same as the background. In the JSCPA approach, the bit and power allocations are done jointly. Thus, the JSCPA approach is able to adapt the power per packet, making the probability of loss dependent on the relative importance of each packet, as shown in Figs. 4e and 4g.

JOINT SOURCE-CHANNEL CODING AND POWER ADAPTATION

In an energy-efficient wireless video system, transmission power needs to be balanced against delay to achieve the best video quality. The authors in [8] studied the problem of joint source-channel coding and power adaptation, when the channel parameters consist of both channel coding and power allocation. Error-resilient source coding is achieved by mode selection and the use of RCPC channel codes, with the power assumed to be adjustable in a discrete set at the physical layer.

Source-channel coding and power adaptation can also be used in a hybrid wireless/wireline network, which consists of both wireless and wired links, as shown in Fig. 5. In this case, different channel codes can be used to combat different types of channel errors: packet dropping in the wire-line network and bit errors in the wireless link. In [14] Reed-Solomon codes are used to perform interpacket protection at the link layer and RCPC codes to perform intra-packet protection at the physical layer. The selection of channel codes is jointly considered with source coding parameter selection and power adaptation to achieve energy-efficient communication. As we see, cross-layer design is a powerful approach for dealing with different types of channel errors in such a hybrid wireless/wireline network.

Joint Source Coding and Data Rate Adaptation

Joint source coding and transmission rate adaptation has also been studied as a means to provide energy efficient video communications. In order to maintain a certain probability of loss, the energy consumption increases as the transmission rate increases. Therefore, in order to reduce energy consumption, it is advantageous to transmit at the lowest rate possible [11]. In addition to affecting energy consumption, the transmission rate also determines the number of bits that can be transmitted within a given period of time. Thus, as the transmission rate decreases, the distortion from source coding increases. Joint source coding and transmission rate adaptation techniques adapt the source coding parameters and the transmission rate in order to balance energy consumption against end-to-end video quality. In [3] the authors consider optimal source coding and transmission rate adaptation. Stochastic dynamic programming is used to find an optimal source coding and transmission policy based on a Markov chain channel model. A key idea in this work is that the performance can be improved by allowing the transmitter to suspend or slow down transmissions during periods of poor channel conditions, as long as the delay constraints are not violated.

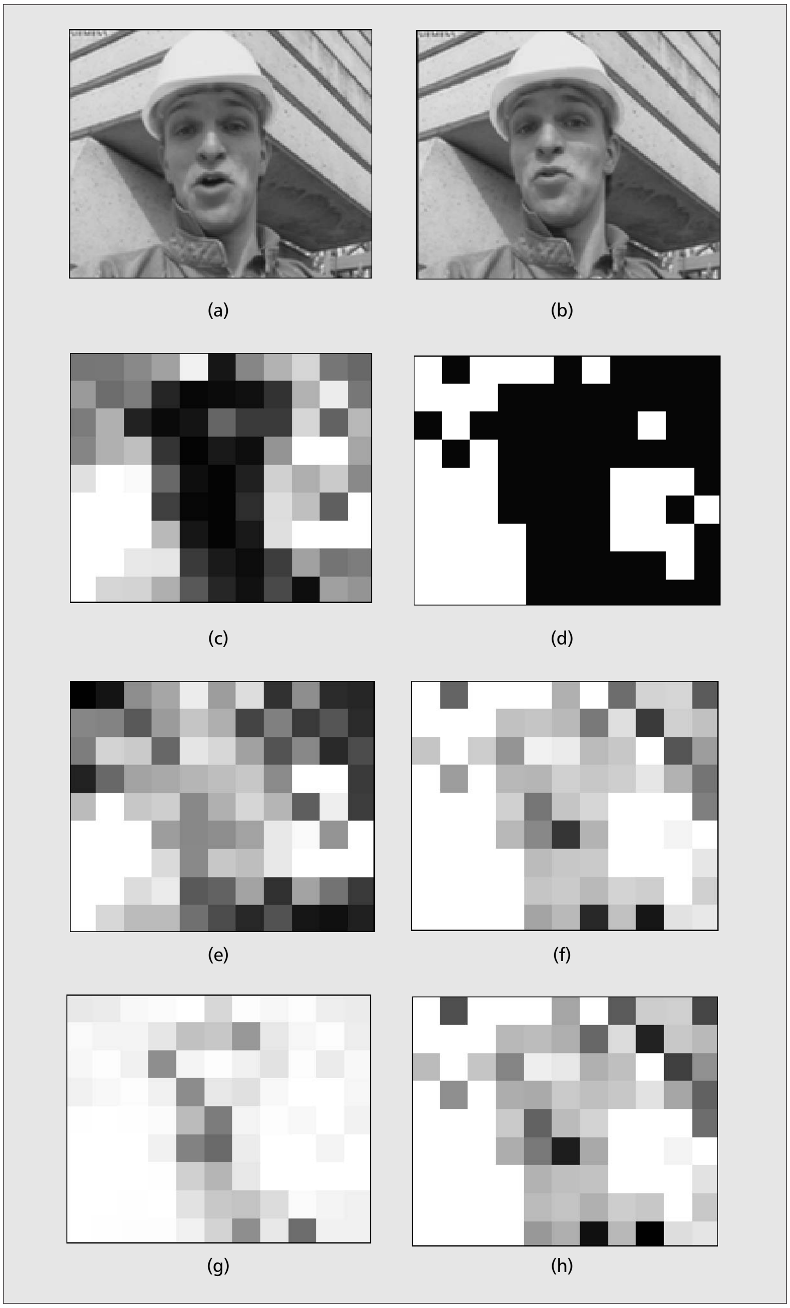


Figure 4. *Frames a) 42 and b) 43 in the original "Foreman" sequence. Probability of packet loss per MB for frame 43 using c) the JSCPA approach; d) the ISCPA approach. Darker MBs correspond to a lower probability of packet loss. Macroblocks that are not transmitted are shown in white. Bits per MB using e) the JSCPA approach; (f) the ISCPA approach. Darker MBs correspond to more bits. Transmission energy per MB using (g) the JSCPA approach; (h) the ISCPA approach. Darker MBs correspond to more transmission energy.*

Conclusions and Future Directions

A key factor determining the effectiveness of a mobile device for wireless video transmission is its energy management strategy. This article presents an overview of energy-efficient system design for video transmission over an uplink wireless channel. A general framework for studying this problem has been presented, where the goal is to achieve the best video delivery quality with the minimum energy consumption. We first discussed the key adaptation components that affect video delivery quality and energy consumption in a wireless video communications system. We further analyzed in detail how these adaptation components can be manipulated to achieve energy efficiency. Several examples from recent research studies were used to clearly illustrate the advantages of jointly considering error-resilient source coding and channel adaptation parameters including power, FEC, and rate adaptation.

Jointly adapting components from different communication layers requires more effective communications between those layers. In the traditional layered protocol stack, each layer is independently optimized or adapted to the changing network conditions. The adaptation, however, is very limited due to the limited interactions between layers. Therefore, more efficient adaptation requires cross-layer design, not

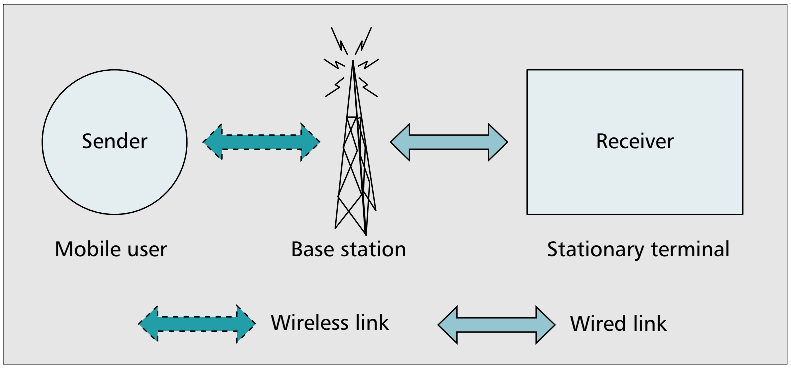


Figure 5. *Video transmission over a hybrid wireless/wireline network.*

only from the video applications' side [2], but also from the network protocol's side [15]. As illustrated in this article, cross-layer design for video transmission aims to improve the overall performance and energy efficiency of the system by jointly considering the video encoder and multiple protocol layers. In this article we assume that the required channel state information is available at the controller that performs joint source-channel adaptation. Another important design issue that is outside the scope of this article is managing the cost of acquiring and transmitting the necessary channel state information between various network layers. In the future, cross-layer design is expected to play an important role in the development of new wireless video communication systems, including 4G wireless networks.

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