Power-Aware Mobile Multimedia: a Survey (Invited Paper)

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***Abstract*— With the fast-paced development of computing technologies, mobile devices have almost sufficient computation and communication capabilities to support mobile multimedia applications such as multimedia streaming, VoIP, and mobile TV. However, most existing mobile devices are powered by battery with limited energy resource. To support multimedia on battery-powered mobile devices, how to efficiently utilize the limited power source and other limited network resources has become one of the major challenges in mobile multimedia system design. It has been shown that achieving a satisfactory user experience needs a systematic consideration of both video source adaptation and network transmission adaptation, indicating that the core of mobile multimedia system design is how to achieve a good balance of the power consumption between computation usage and communication usage. In other words, it depends on how to jointly select video source parameters and channel parameters based on the video content characteristics, available network resources, and underlying network conditions, given the fact that the power management schemes as well as the nonlinear battery effects also affect the system power consumption of mobile devices. In this paper, we review the recent advances in power-aware mobile multimedia, especially the adaptation technologies applied in video coding and delivery. In addition, the major research challenges in the field are demonstrated and discussed, which include power-management for mobile devices, rate-distortion-complexity optimized video codec design, and computational complexity and power aware cross-layer design and optimization. At the end, we propose a number of future research directions for audiences to continue investigation in this field.**

***Index Terms*— Power-aware multimedia, H.264, power management, joint source-channel coding, power adaptation, cross-layer design and optimization**

I. INTRODUCTION

In recent years, the computation and communication technologies have been advanced to effectively integrate multimedia functions into battery-powered mobile multimedia devices, such as mobile TVs, PDAs, and cell phones [1]. On the other hand, due to the relatively slow development on battery technologies, battery capacity is still very limited [2], [3]. Thus, the gap between power consumption of mobile multimedia and the limited power source has been widened. Moreover, better video viewing experience calls for better compression algorithm, data rate adaptation, and adaptive error control as well as error concealment technologies. Thus, the core design problem of mobile multimedia becomes how to achieve a good balance of the power consumption between computation usage and communication usage in mobile multimedia.

Understanding power consumption in mobile multimedia is the key for efficient power management of the next-generation mobile multimedia. In general, power consumption of mobile multimedia is mainly on computation, communication, and I/O devices [4]. Since major signal processing units in codec such as motion estimation and compensation, forward and inverse discrete cosine transforms, and quantization require a significant number of calculations, computational power consumption is of special interest. Due to the fact that each signal processing function unit of a codec can operate in multiple modes, how to select the operation mode of each function unit to optimally tradeoff the codec power consumption and the corresponding video distortion has become a great design challenge. On the other hand, experiment results show that video encoding consumes about 2/3 of the total power for video communications over Wireless LAN with relatively high distortion [5], and this ratio will increase when the required video distortion becomes lower [6]. Furthermore, due to the time-varying channel, power consumption on communication is another important concern. On the whole, given a required video quality level, to generate a lower video data rate, higher compression by advanced video coding algorithms are needed, leading to higher processing complexity and more power consumption on computation. Thus, the computational power consumption is

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a decreasing function of the compression rate. For higher transmission rate, we need more transmission power to keep the same bit-error-rate performance. In this sense, there is an intrinsic contradiction on power consumption allocation between computation and communication.

To minimize the total power consumption of mobile multimedia, we need to dynamically balance the power consumption between the computation usage and communication usage. Due to the scalability of a modern video codec, power allocation between computation and communication can be adaptive [7]–[9]. For example, in H.264 main profile, intra prediction can operate in 13 modes [10]. Another example is that inter prediction allows a variety of operational points such as multiple reference frames, weighted prediction and quarter pixel accurate motion estimation, and variable block size for motion compensation [6]. Furthermore, power consumption on communication can also be controlled by adjusting the data rate of the encoder, source channel coding schemes, and the transmission range of a transmitter. In summary, the design goal of mobile multimedia is to determine the optimal power allocation between computation and communication and to minimize the total power consumption, while keeping the perceived video distortion at a satisfied level.

In this paper, we will review the recent major advances in power-aware mobile multimedia with focus on power-aware video coding and video delivery. We aim at providing a survey on the solutions to major problems of this field, such as how various source parameters (e.g., video coding, video object extraction, and video summarization) and channel parameters (e.g., selection of transmitter power levels, selection of modulation and channel coding schemes, scheduling) are jointly optimized to adapt to the video content characteristics and the underlying network conditions to enable energy-efficient mobile multimedia, and how to assign transmission power and other network resources among multiple mobile users to achieve the minimum interference to each other. Moreover, power management schemes and the nonlinear battery effect will also be discussed to reduce the power consumption of the system and prolong the battery operating time. Furthermore, we will present the remaining major research challenges in the field of power-aware mobile multimedia. Future research directions will also be provided to advance further research efforts in this field.

The rest of the paper is organized as follows. In Section II, we present a power-aware wireless video communication system. Power-aware video coding is reviewed and discussed in Section III. Section IV reviews and investigates power-aware video delivery. The main research challenges and future research directions are provided in Section V. We conclude the paper in Section VI.

II. Power-Aware Wireless Video Communication System

A conceptual power-aware mobile multimedia system is illustrated in Figure 1. At the transmitter device, different video source adaptation methods, such as typical prediction and quantization, scalable video coding [11], transcoding [12], object-based video coding [13], and summarization [14], may provide different video compression rate based on the video content to match the receiver capability. Then, the compressed data packets are transmitted over wireless links. To combat the lossy nature of a wireless channel, adaptive modulation and channel coding schemes as well as transmitter power at the physical layer can be adjusted based on the channel state information (CSI). Mobile multimedia receiver devices of demodulate the received bit stream, perform error detection and correction, decode the received bit stream and display reconstructed video clips. Mobile receiver devices may interact with the transmitter devices to adaptively adjust the compression rate to provide differentiated services following the interactive activities of end users. Note that mobile multimedia devices are powered by battery, which is not an ideal energy source, since it tends to provide less energy at higher discharging currents. To minimize the total consumed battery energy for delivering a video clip with satisfied quality, joint rate-distortion-complexity optimization to prolong the battery operating time is necessary.

A. Understanding Power Management in Mobile Devices

Since the battery technology cannot satisfy the growing power demand of mobile multimedia devices, power management technology is needed to increase system power efficiency. However, efficient use of the limited battery energy is one of the major challenges in designing mobile multimedia communication devices with limited battery energy supply. This is because 1) real-time multimedia is bandwidth-intense and delay-sensitive, and battery may need to continuously discharge, 2) wireless channel dynamically varies over time and space due to fast and large-scale channel variations, 3) different mobile devices have different limited processing power levels, limited memory and display capabilities, and limited battery energy supply due to the size and weight constraints, 4) video quality does not increase linearly as the complexity increases, and 5) battery discharge behaviors are nonlinear. Since the performance of each part in the mobile multimedia device is dynamic and heterogeneous, all these innate conflicts induce the major research challenges in designing these mobile multimedia devices. Therefore, how and when to apply a particular power reduction technique is a challenging problem. However, there does not yet exist a systematic method for the power management of mobile devices in real-time multimedia applications.

1) Dynamic Voltage and Frequency Scaling: The multimedia content is time-varying as well as delay-sensitive. As a result, to maintain a dynamic balance between the operating level of the processor and the QoS of multimedia application is challenging. In [15], an offline linear programming method has been proposed to determine the minimum energy consumption for processing multimedia tasks under stringent delay deadlines. In [16],

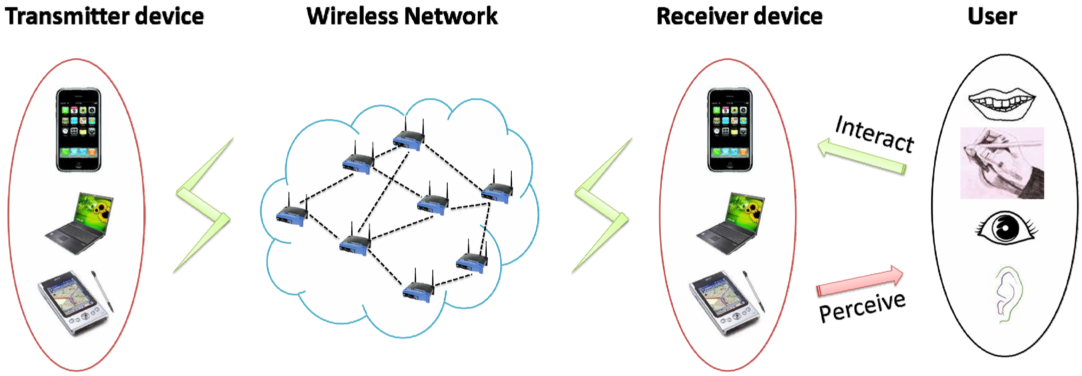

Figure 1. A conceptual power-aware mobile multimedia system.

an optimal frequency was assigned by a buffer-controlled DVS framework to optimally schedule active and passive states for a video decoding system. The work in [17] uses the workload of a video application to determine the frequency and voltage of a processor for playing streaming video with less power consumption while minimizing data losses. The proposed DVS algorithm has been implemented on PXA270 processor with Linux 2.6 kernel. In [18], both CPU and multimedia accelerator have been considered to reduce the power consumption of handhold systems. In [19], based on the statistical analysis of more than 600 processor load trace files, a novel interval-based DVS scheme has been proposed to handle the non-stationary behavior by using an efficient online change detector and important parameters, and thereby the penalty incurred by DVS can be efficiently controlled.

2) Maximizing Available Battery Capacity: Due to the nonlinear battery effects, the actual battery capacity of a full charged battery is always less than its theoretical capacity. Battery capacity decreases as the discharging current increases, and will recover the decreased capacity when the battery has been rested or discharged at a low current rate. Therefore, useable battery capacity is significantly affected by the discharge current shape. As a result, a minimum-power-consumption policy does not necessarily result in the longest battery operating time. Battery-aware scheduling schemes attempt to tailor the current of a device to match the optimal discharge rate of the battery. However, for the run-time and delay sensitive multimedia application, how to achieve the best tradeoff between the discharge current shape and video quality is extremely challenging. Normally, the following guidelines are used: 1) For a set of scheduleable tasks with different current costs, scheduling them in the decreasing order of current costs is the optimum battery solution as shown in Figure 2 [20]; 2) for a given task t to be executed before a given deadline d, it is better to lower the frequency and run without giving an idle slot than to give an idle slot and run at a higher frequency as shown in Figure 3 [20].

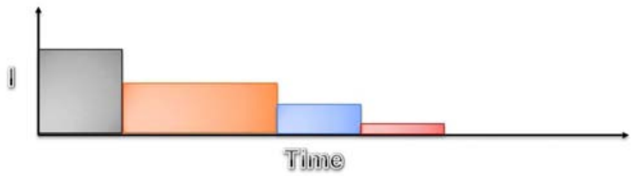

Figure 2. Battery-aware scheduling guideline 1.

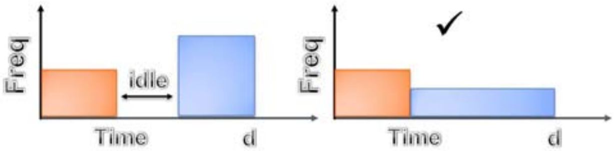

Figure 3. Battery-aware scheduling guideline 2.

3) Power-Aware Transmission and Buffer Management: Wireless network interface cards (NIC) have multiple operation modes such as sleep, idle, transmit, and receive. Each mode has different power consumption. Thus, significant energy saving can be achieved by switching the operation mode from idle to sleep or even off during idle periods. However, an extra amount of power consumption is spent to activate or deactivate the electronic components for mode transition. For multimedia applications, how to optimally set the transition point of the NIC is a crucial problem. Bursty traffic could combine the short idle intervals into longer ones to reduce the number of mode transition [21], [22]. Consequently, power consumption on mode transition is reduced. In [23], the minimum buffer size on the receiver side was determined to achieve the maximum energy saving under three cases: single-task, multiple subtasks, and multi-task. In [24], a power saving approach using a realistic network framework in the presence of noise has been analyzed. The transcoded video is buffered by proxy middleware buffers, and then the buffered video is transferred in bursts over a given time. Thus, the NIC modes are alternatively switched between active and idle to save power. In [25], a power-aware transmission scheme can switch off the card while frames are being played back until a low-threshold level is reached in the client buffer. In [26], the video data is queued in a buffer and sent by bursts at a longer interval. Consequently, much energy on transmission can be saved.

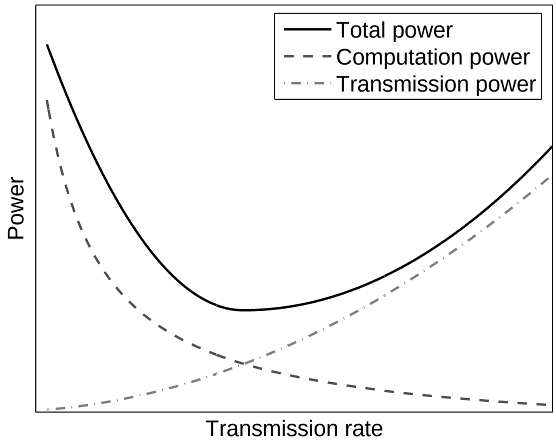

Figure 4. Power consumption on computation and communication in multimedia communication.

B. Power Consumption Tradeoff between Computation and Communication

The total power consumed by a mobile device is mainly composed of the power to code the source at the application layer and the power to transmit the coded bits at the physical layer. As shown in Figure 4, a high compression ratio will increase the encoding computational complexity and require more computational power. For desired distortion, the computational power is a decreasing function of the coded bit rate. On the other hand, to maintain the desired bit error rate, adequate transmission power is needed. Therefore, the total power consumption on coding and transmitting video frame k is a convex function of the transmission rate, which can be denoted as:

$$P_{\text{total}}^k = P_C^k(R) + P_T^k(R) \tag{1}$$

where P_C^k is the consumed power in coding the k^{th} frame. P_T^k is the consumed power in transmitting coded bits at transmission rate R.

Overall, all practical communication networks have limited bandwidth and are lossy by nature. Furthermore, wireless channel conditions and multimedia content characteristics may change continuously, requiring constant value updates of source and channel parameters. In addition, multimedia streaming applications typically have different quality of service (QoS) requirements with respect to packed loss probability and delay constraints. Therefore, the total power consumption of mobile multimedia devices can be minimized by taking advantage of the specific characteristics of video source and jointly adapting video source coding decisions, transmission power, and modulation and coding schemes.

Generally, to minimize the total power P_{tot}, the source coding parameters S, channel (transmission) parameters C, network interface card (NIC) setting N, and decoder parameters (e.g., error concealment strategy) Q have to be jointly considered to satisfy distortion and delay constraints. The goal of power consumption tradeoff between computation and communication is to minimize the total consumed power. The problem can be stated as:

$$\min P(S,C,N,Q)$$
$$s.t. \begin{cases} D_{tot}(S,C,N,Q) \le D_0 \\ T_{tot}(S,C,N,Q) \le T_0 \\ C_{tot}(S,C,N,Q) \le C_0 \end{cases} \tag{2}$$

where D_0 is the maximum distortion to ensure the satisfied video quality. T_0 is the end-to-end delay constraint imposed by the given video application. C_0 is the maximum computational complexity that the mobile multimedia device can provide. The selection of S, C, N, and Q will affect the end-to-end distortion D_{tot}, delay T_{tot}, and computational complexity C_{tot}.

A dual formulation to (2), is to minimize the received video distortion D_{tot} with constraints of delay, computational complexity, and power consumption.

$$\min D_{tot}(S,C,N,Q)$$
$$s.t. \begin{cases} P_{tot}(S,C,N,Q) \le P_0 \\ T_{tot}(S,C,N,Q) \le T_0 \\ C_{tot}(S,C,N,Q) \le C_0 \end{cases} \tag{3}$$

where P_0 is the maximum allowable power consumption.

To solve the problem in (2), we need to understand 1) how source adaptation at a video codec affects the computational complexity and the achieved video quality; 2) how transmission adaptation affects the power consumption on transmission and the obtained video quality. We will discuss these two issues in the following sections in detail.

III. Power-aware Video Coding

Video coding achieves high compression efficiency, and enables high resolution videos to be played by mobile multimedia devices. However, the high coding efficiency of video coding is achieved at the cost of high computational complexity. As a result, a significant burden is put on the processor, which is challenging for mobile multimedia devices with limited processing capabilities and battery energy [27], [28].

A. Estimation of Codec Power Consumption by Its Predictable Computational Complexity

The video encoding and decoding flexibility provides a variety of multimedia implementation platforms, and enables significant tradeoff between video coding quality and computational complexity. In order to optimally select the optimal operating point of a multimedia application for a specific system, the rate-distortion and the complexity characteristics of the operational video coders should be accurately modeled. For example, the computational complexity of an H.264/AVC baseline decoder is mainly determined by two major components: time complexity and space (or storage) complexity [29]. The computational complexity of each module can be found in [30]–[34]. A tool for the complexity analysis of C reference description has been proposed in [35]. In [36], a generic rate-distortion-complexity model has been proposed to generate digital item adaptation descriptions for image and video decoding algorithms running on various hardware architectures. The model can estimate average decoding complexities as well as the transmission bit-rate and content characteristics. As a result, the receiver can negotiate with the media server/proxy to have a desired complexity level based on their resource constraints. Based on operational source statistics and off-line or online training to estimate the algorithm and system parameters, a stochastic model has been proposed in [37]. An analytical rate-distortion-complexity modeling framework for wavelet-based video coders has been proposed in [38]. In [39], Gaussian mixture models and an expectation-maximization algorithm have been proposed to jointly estimate the execution time required by each video decoder module.

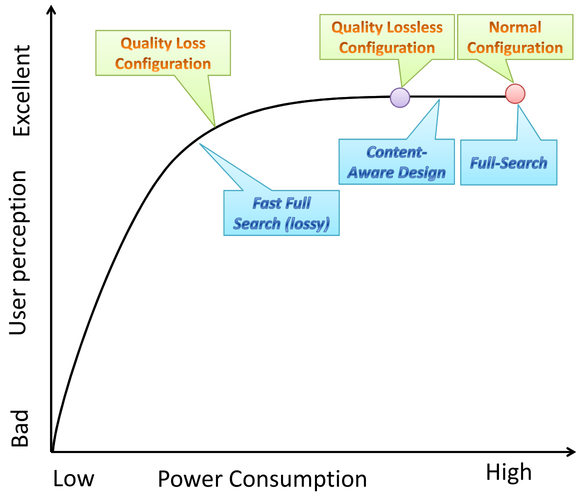

Figure 5. *User perception versus power consumption [1].*

B. Computational Complexity Reduction by Approximation and the Corresponding Challenges

The computational complexity can be scalable in various aspects. Based on the observations: 1) not every round of local refinement of fast motion search algorithms can achieve equally good sum of absolute difference operations; 2) motion estimation of smaller block modes is often redundant. A joint rate-distortion-complexity optimization framework has been proposed to balance the coding efficiency and the complexity cost of the H.264 encoder in [40]. The method can cutoff the complexity-inefficient motion search rounds, skip redundant motion search of small block modes, and terminate motion search at the optimal rate-distortion-complexity points. In [41], scalable memory complexity reduction has been considered via recompressing I- and P- frames prior to motion-compensated prediction. A simple rate-distortion-complexity adaptation mechanism for wavelet-based video decoding based on the number of decoded non-zero coefficients used prior to the inverse discrete wavelet transform has been proposed in [42]. A real-time video streaming system based on the complexity model in [36] has been proposed in [43].

In addition, choosing the right set of encoder parameters results in efficiently coded video. However, joint rate-distortion-complexity analysis of H.264 is complex due to the large number of possible combinations of encoding parameters. As a result, exhaustive search techniques is infeasible in encoder parameter selection. Several heuristic algorithm has proposed to reduce computational complexity in video coding. In [44], a subset of coding parameter choices is selected and algorithmic simplifications are enforced, and then the effect of each parameter choice and simplification on both performance and complexity reduction is quantified. Rate-distortion-complexity optimization of integer motion estimation in H.264 has been discussed in [45]. In [46], the computational complexity and distortion are estimated based on the encoding time and mean squared error measurement. Furthermore, the generalized Breiman, Friedman, Olshen, and Stone (GBFOS) algorithm [47] has been used to efficiently obtain parameter settings so that obtained Distortion-Complexity points are close to optimal. In [48], a non-heuristic non-probabilistic approach based on non-additive measure quantitatively captures the dynamic interdependency among system parameters under uncertainties, which is possible method to effectively and efficiently optimize codec parameters.

Furthermore, the quality performance does not increase linearly as the complexity increases. There is a saturation point of quality improvement. Beyond that point, significant computational effort may get little performance improvement, which makes joint rate-distortion-complexity analysis significantly challenging. Moreover, the video content and their characteristics can be very different sequence by sequence, or even frame by frame. The video content can be slow motion such as head-and-shoulder video, fast motion such as sport videos, or global motion. A video frame may contain a simple scene with a few object motions or a complex scene with many object motions [1].

The goal of power-aware codec design is to optimally select codec modes to minimize the power consumption on computation with the desired visual quality and delay constraints. However, joint rate-distortion-complexity optimization makes our optimization framework even more challenging as the state space increases significantly if more options are considered in the optimization. In that sense, designing deterministic power-aware codec algorithms are extremely challenging. Therefore, various heuristic approaches have been proposed to design power-aware codec. As shown in Figure 5 [1], selection of different video compression algorithms will bring about different levels of video quality and power consumption. Content aware algorithms can reduce the power consumption with the lossless user perception, while lossy fast algorithm can adaptively tradeoff the user perception with power consumption. Consequently, Power-aware codec can dynamically select video compression algorithms to reduce power consumption based on user satisfaction, video content characteristics, as well as battery states. In [49], a configurable video coding system is proposed, which uses an exhaustive search and the Lagrangian multiplier method to optimize the performance and computational complexity. In [1], power-aware concepts and considerations of specific conditions such as different battery status, signal content, user preferences, and operating environments have been proposed. The proposed system can dynamically set the codec mode based on different battery situations to prolong the battery operating time. A conceptual example of power-aware video coding is shown in Figure 6, where higher resolution is adopted under full battery situation while lower resolution is used under lower battery situation. In [50], an embedded compression algorithm and VLSI architecture with multiple modes for a power-aware motion estimation has been presented, which reduces external access caused by video content, and further reduces the power consumption of the codec. In [51], an adaptive content-based sub-sampling algorithm has been proposed. The architecture adaptively performs graceful tradeoffs between power consumption and compression quality. The methodology of power-aware motion estimation has also been addressed in literature. In [52], hardware-oriented algorithms and corresponding parallel architectures of integer ME and fractional ME have been proposed to achieve memory access power reduction and provide power scalability and hardware efficiency, respectively.

C. Scalability Video Coding – Another Way to Reduce Computational Complexity

Scalability Video Coding (SVC) provides the capability to easily and rapidly fit a compressed bit stream with the bit rate of various transmission channels and with the display capabilities and computational resource constraints of various receivers. This is achieved by structuring the data of compressed video bit streams into layers. The base layer bit streams correspond to the minimum quality, frame rate, and resolution, which provides basic video quality and must be transferred, and determines the minimum power needed to drive the codec [53], [54]. The enhancement layer bit streams represent the same video at gradually increased quality and/or increased resolution, and/or increased frame rate, which provides a flexible coding structure for temporal, spatial, and quality scalability. Properly enabling the enhancement layer is able to balance the video quantity and computational complexity so as to provide a power-aware feature for codec design.

For mobile devices, throughput variations and varying delay depend on the current reception conditions, and need to be considered. Scalability of a video bit stream provides various media bit rates to match device capability without the need of transcoding or re-encoding [55]. In [56], video scalable coding can intelligently thin a scalable bit-stream. In [55], [57], [58], bit rate scalable media may combine with unequal error protection, selective retransmission, or hierarchical modulation schemes to strongly protect the important part of the scalable media for overcoming worst-case error scenarios and give less protection to the enhancement layer in order to overcome the most typical error situations. Thus, video quality may gracefully degrade to adapt the channel conditions. In [59], a video bit rate adaptation method relying on a scalable representation drastically reduces computational requirement in network element.

IV. Power-Aware Video Delivery

Transmitting video over wireless channel faces a unique challenge. Due to the shadowing and multipath effects, wireless channel gain varies over time, and thus signal transmission is significantly unreliable. Therefore, constant power cannot lead to the best performance. Although the reliability of signal transmission can be increased by increasing the transmitter power, most of mobile multimedia devices are powered by battery with limited power source, making it an unpractical solution. How to achieve satisfied QoS over a fading channel with the minimum power consumption is critical for mobile multimedia device design.

In this section, we examine and review the most popular techniques for power-aware video delivery in mobile multimedia applications, i.e., joint source-channel coding and power adaptation, and cross-layer design and optimization. We present a general framework that takes into account multiple factors, including source coding, channel resource allocation, and error concealment, for the design of power-aware wireless video delivery systems.

A. General Framework

Since video encoding and data transmission are the two dominant power-consuming operations in wireless video communication [5], we focus on how to jointly optimize source coding parameters S (e.g., prediction mode and quantization step size) and channel parameters C (e.g., channel codes, modulation modes, transmission power levels, or data rates) in a power-aware video communication system to achieve a targeted video quality or energy usage. Moreover, the delay performance is more crucial than the computational complexity in real-time video delivery. Therefore, from (2) and (3), the problem of power-aware wireless video delivery can be formally stated as

$$\begin{aligned} &\min_{[S,C]} E_{\mathrm{tot}} \\ &\quad s.t.: D_{\mathrm{tot}}(S,C) \le D_0; \\ &\qquad\quad T_{\mathrm{tot}}(S,C) \le T_0, \end{aligned} \tag{4}$$

and

$$\begin{aligned} &\min_{[S,C]} D_{\mathrm{tot}} \\ &\quad s.t.: E_{\mathrm{tot}}(S,C) \le E_0; \\ &\qquad\quad T_{\mathrm{tot}}(S,C) \le T_0, \end{aligned} \tag{5}$$

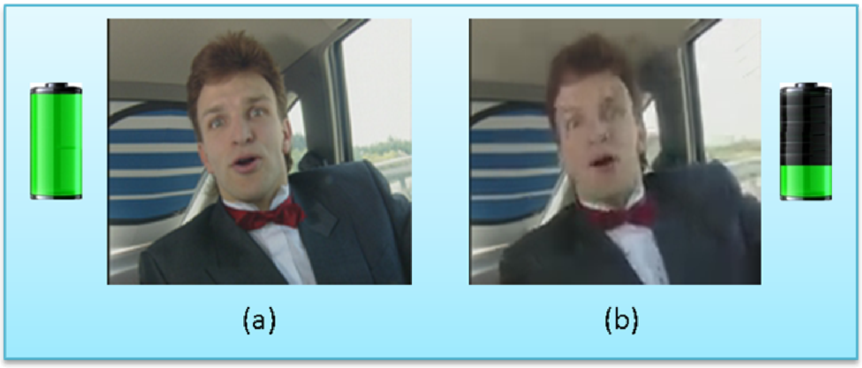

Figure 6. *Power-aware multimedia example: scalable visual quality and power consumption modes for different battery situations. (a) Full battery mode, (b) Low battery mode. Note that the right image is an upscaling image that coded in lower resolution.*

respectively, where E_0 is the maximum allowable energy consumption, T_0 is the end-to-end delay constraint imposed by the application, and D_{tot} is the end-to-end distortion. 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 end-to-end distortion $E[D_k]$, the end-to-end delay T_{tot}, and the total energy E_{tot} in Eq. (5) are all affected by parameters S and C. We use $D_{\text{tot}}(S, C)$, $T_{\text{tot}}(S, C)$, and $E_{\text{tot}}(S, C)$ to explicitly indicate these dependencies. The expected distortion for the kth packet can be written as

$$E[D_k] = (1 - p_k)E[D_k^r] + p_k E[D_k^l], \tag{6}$$

where p_k is the probability of loss for the kth packet, $E[D_k^r]$ is the expected distortion if the packet is received correctly, which accounts for the distortion due to source coding as well as error propagation caused by interframe coding. $E[D_k^l]$ is the expected distortion if the packet is lost, which accounts for the distortion due to concealment. The probability of packet loss p_k depends on the channel state information (CSI), transmitter power, modulation and channel coding used. Given transmission rate R, the transmission delay needed to send a packet of L bits is $T = \frac{L}{R}$. The energy needed to transmit the packet with transmission power P is given by $E = \frac{PL}{R}$.

B. Joint Source-Channel Coding and Power Adaptation

In the literature, joint source-channel coding and power adaptation is a critical technique to achieve power-aware video delivery. In this section, we consider several examples to show how the source coding and channel parameters including the transmission power can be jointly selected to achieve energy-efficient video coding and transmission.

A joint source-channel coding and power adaptation system is depicted in Figure 7 [4], where source coding parameters at the encoder and channel parameters at the transmitter are jointly selected by the controller based on the source content, the error concealment strategy and the available CSI. In power-aware wireless video delivery systems, transmitter power adaptation and channel coding are two powerful techniques to overcome bit errors caused by unreliable wireless network links. Taking advantage of the specific characteristics of video source and jointly adapting video source coding decisions with transmission power, modulation and coding schemes can achieve substantial energy efficiency compared with non-adaptive transmission schemes [60]–[63]. The authors in [60] proposed a framework where source coding, channel coding, and transmission power adaptation are jointly designed to optimize video quality given constraints on the total transmission energy and delay for each video frame. In addition to the used rate-compatible punctured convolutional (RCPC) codes, transmission power of each packet is also adapted to decrease the loss probabilities of packets. The work in [61] jointly considered optimal mode and quantizer selection with transmission power allocation.

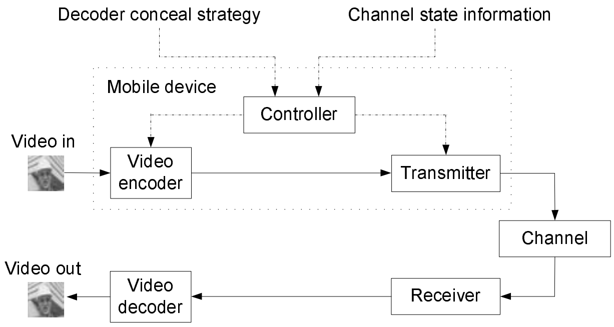

Figure 7. *Block diagram of joint source-channel coding and power adaptation systems.*

To illustrate performance gain of joint adaptation of the source coding and transmission parameters in power-aware mobile video systems, we present some experimental results, which are discussed in detail in [61]. In the experiment, a joint source coding and transmission power allocation (JSCPA) approach is compared with an independent source coding and power allocation (ISCPA) approach in which S and C in Problem (5)

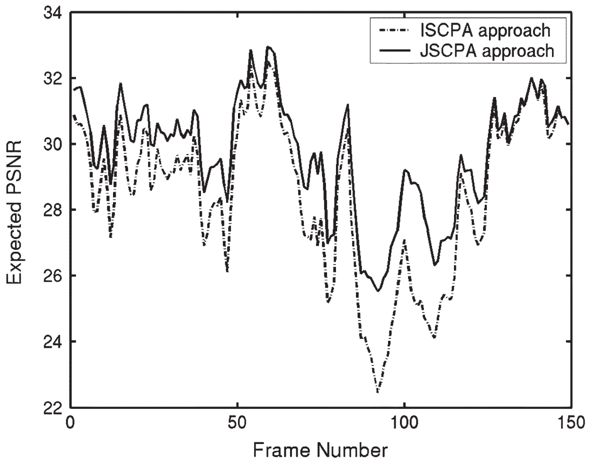

Figure 8. *Expected PSNR/frame for the ISCPA and JSCPA approaches.*

are independently adapted. It is important to note that both approaches use the same transmission energy and delay/frame. In addition, the *generalized skip* option is used by the JSCPA approach to improve efficiency [61]. The idea is that if the concealment of a certain packet results in sufficient quality, then the algorithm can intentionally not transmit this packet in order to allocate additional resources to packets that are more difficult to conceal. In Figure 8, we plot the expected PSNR/frame of both approaches for the "foreman" test sequence coded at 15 frames/s (fps). We observe that the JSCPA approach achieves significantly higher quality (expected PSNR)/frame than the ISCPA. Due to the independent operation between the video encoder and the transmitter in the ISCPA approach, the relative importance of each packet, i.e., their contribution to the total distortion, is unknown to the transmitter. Therefore, the transmitter treats each packet equally and adapts the power in order to maintain a constant probability of packet loss. The JSCPA on the other hand is able to adapt the power/packet and, thus, the probability of loss, based on the relative importance of each packet. For example, more power can be allocated to packets that are difficult to conceal. Figure 9 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.

To sum up, power-aware joint source channel coding usually should implement the following three tasks: 1) Finding an optimal power adaptation scheme and bit allocation between source coding and channel coding for given channel loss characteristics; 2) Optimizing the source coding to reduce the computational complexity and achieve the target source rate, and 3) Optimizing the channel coding to achieve the required robustness [64], [65]. Although, these three tasks are separately mentioned, they are essentially correlated. Properly choosing the mode and coding rate of codec, channel coding schemes, and transmission power can reduce the total power of the system. In [66], a power-minimized bit-allocation scheme has been proposed to process power for source coding and channel coding as well as transmission power for a given video quality. In [67], the authors proposed to jointly adjust the operating parameters of the source coder, channel coder and transmitter to minimize the total power dissipation, while keeping the end-to-end distortion of the source constant. In [5], source coding parameters are used to control the tradeoff between the power consumption and coding efficiency, which can be achieved by controlling how often to conduct motion estimation. In [68], properly choosing the encoding modes and corresponding coded modulation configurations to keep the same distortion has been discussed. In [14], parameters of video coder, channel coder, and transmit power were jointly optimized to minimize the power consumption. In [24], faster decompression rates saved significant power via reduced memory accesses. Multi-stage coded modulation was utilized to accommodate rates in the different modes. By judiciously selecting operation modes in response to mobile environment, lower power consumption can be achieved.

C. Power-Aware Cross-Layer Design and Optimization

Due to limited adaptation to dynamic wireless link conditions and interaction between layers, traditional layer-separated protocols and solutions fail to provide QoS for mobile multimedia applications. Therefore, more efficient adaptation requires cross-layer design, not only from the video applications' side, but also from the network protocol's side. Cross-layer design for power-aware multimedia aims to improve the overall performance and energy efficiency of the system by jointly considering the video encoder and multiple protocol layers.

Figure 10 shows a block diagram of cross-layer design and optimization for general mobile multimedia systems [69], where a cross-layer controller is designed at the sender (the source node) to provide the following functionalities: 1) interact with each layer and obtain the corresponding managerial information, such as the expected video distortion from the encoder and the network conditions from lower layers; 2) perform optimization and determine the corresponding optimal values of control variables residing in various layers. The control variables may include, but not limited to, source coding parameters S at the application layer and channel parameters C at the lower layers which include the sending rate at the transport layer, transmission path at the network layer, retransmission limit and channel coding at the data link layer, and modulation and transmitter power at the physical layer. In this cross-layer framework, network conditions, such as CSI, packet loss rate, network throughput, network congestion status, etc., are all assumed to be available to the controller. How to timely acquire and deliver these network condition information to the controller still remains a challenging task.

Power-aware cross-layer design and optimization for mobile multimedia has received a lot of research efforts. Various design techniques and optimization methods have

(a) Original (b) Proposed (c) Delay-based

Figure 9. 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.

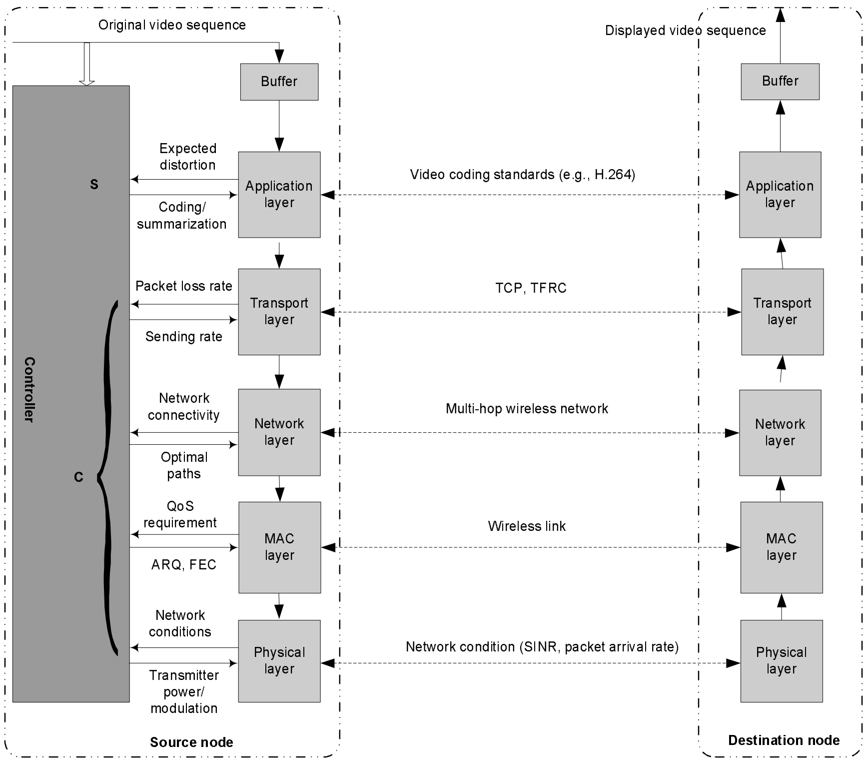

Figure 10. *Block diagram of cross-layer design and optimization in power-aware mobile multimedia applications.*

been developed. First, almost all the work of joint source-channel coding and power adaptation [4], [60] reported in Section IV-B adopted the approaches of cross-layer optimization, where video source coding and communication decisions have been jointly considered. For example, the work in [60] jointly considered the error resilient source coding at the encoder, transport-layer FEC, link-layer FEC, and power adaptation at the physical layer to minimize the total end-to-end distortion subject to the transmission delay and battery energy constraints. Lagrangian relaxation and dynamic programming were adopted to obtain the optimal solution.

Besides source coding adaptation, other video source adaptation techniques can also be considered in power-aware cross-layer optimization, such as scalable video stream extraction [11], [70]–[72], transcoding [12], object-based video coding [13], and summarization [14], [73]. For example, the work in [14] studied energy-efficient video summarization and transmission where the tradeoffs between the summary transmission energy cost and the summarization distortion were explored. The authors in [73] discussed video source adaptation based on content summarization with power constraint for video streaming in wireless cellular systems.

Cross-layer optimization for resource allocation and scheduling is another interesting research topic in power-aware mobile multimedia. Plenty of research has focused on multi-user wireless video streaming systems [73]–[76] where the assignments of the transmission power as well as other network resources among multiple users were discussed. For example, the work in [74] studied cross-layer resource allocation for HSDPA downlink multiuser video transmission, where the rate assignment, power assignment, and spreading code assignment among multiple users were jointly optimized to minimize the total expected distortion. In [73], the authors proposed a framework for joint network optimization, source adaptation, and deadline-driven scheduling for multi-user video streaming over wireless networks while taking into account the power constraints imposed by the coexistence of audio users and video users.

V. CHALLENGES AND FUTURE DIRECTIONS

Based on the above discussion, there has been a dramatic advance in the research and development of mobile multimedia systems. However, due to the limited energy supply in mobile device batteries, unfriendly wireless network conditions, and stringent QoS requirement, current research on mobile multimedia still faces several main challenges. In this section, we will list these challenges and point out the corresponding future research directions.

- Power Management in Mobile Devices: Efficient use of the limited battery energy is challenging due to 1) nonlinear discharge behavior of battery; 2) high QoS requirement of realtime multimedia applications; 3) dynamic wireless network conditions, and 4) interactive activities of mobile end-users. Therefore, developing efficient methods for scheduling battery discharge under different battery capacity status and different workload is imperative to prolong the battery operating time.
- Rate-Distortion-Complexity Analysis of Video Codecs: Joint rate-distortion-complexity analysis for advanced video codecs, such as H.264 codec, is complex due to the large number of possible combinations of encoding parameters. It becomes more challenging due to the facts: 1) the quality performance does not increase linearly as the complexity increases, and 2) different videos with different contents and characteristics have different rate-distortion-complexity results. Therefore, developing efficient, accurate and content-aware rate-distortion-complexity analysis models for different video codecs is another challenging research task.
- Computational Complexity: As discussed in Section IV, many source parameters (e.g., prediction mode, quantization step size, and summary choice) and channel parameters (e.g., transmitter power level, modulation, channel coding, and scheduling) could be considered as the control variables for the optimization of mobile multimedia systems. In order to achieve the global optimality, we need to consider control variables and the interactions among them as much as possible. Moreover, the size of the state space of an optimization problem normally increases exponentially with the number increasing of the selected control variables and their operating points. Therefore, to make the best trade-off between the system performance and the computational complexity, how to reduce the computational complexity and how to determine the suitable control variables and their operating points still remain challenging. The authors in [77] introduce a delay-distortion-driven cross-layer optimization framework which can be solved as a large-scale dynamic programming problem. The work presents a new approximate dynamic programming technique based on significance measure and sensitivity analysis for high-dimensional nonlinear cross-layer optimization in support of real-time multimedia applications.
- Network Information Feedback and Cross-Layer Signaling: To perform the best adaptation of control variables to the underlying network conditions, power-aware cross-layer optimization for mobile multimedia requires both accurate and timely feedback of network status information (e.g., CSI and availability information of network resources), as well as more effective communications between network layers. However, in the literature, perfect channel state information is usually assumed available at the controller, which is not real in practice. Therefore, how to manage the cost of acquiring and transmitting the necessary network conditions and how to design cost-effective and time-efficient cross-layer signaling architectures are still the challenging issues. An overview of the research efforts in developing cross-layer signaling architectures is presented in [78].

VI. CONCLUSION

Due to the large number of video source and transmission adaptation parameters, time-varying video content characteristics, uncertain wireless channel conditions, and nonlinear battery effects, enabling power-aware mobile multimedia is extremely challenging. In this paper, we reviewed the latest advances in each component of power-aware mobile multimedia systems with focus on power-aware video coding and power-aware video delivery. Moreover, we focused on the remaining research challenges in the field of power-aware mobile multimedia. Based on the challenge discussions, future research directions were suggested.

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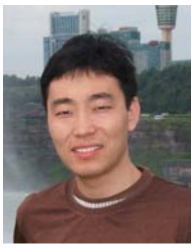

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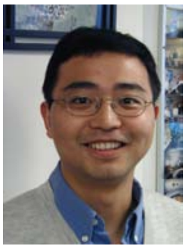

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