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A Survey of Energy-Efficient Compression and Communication Techniques for Multimedia in Resource Constrained Systems

Tao Ma
University of Nebraska-Lincoln, tma@unlnotes.unl.edu

Michael Hempel
University of Nebraska-Lincoln, mhempel2@unl.edu

Dongming Peng
University of Nebraska-Lincoln

Hamid Sharif
University of Nebraska-Lincoln

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Tao Ma, Michael Hempel, Dongming Peng, *Member, IEEE*, and Hamid Sharif, *Senior Member, IEEE*

***Abstract*—Advances in wireless multimedia communication technologies enable new types of pervasive and ubiquitous applications such as mobile health care, environmental monitoring, facility monitoring and traffic surveillance. Among different factors concerned, energy efficiency is one of the most challenging issues in multimedia communication due to the resource constraints, and the requirements for high bandwidth and low transmission delay. In this survey, we provide a broad picture of the state-of-the-art energy efficient techniques that have been proposed in wireless multimedia communication for resource-constrained systems such as wireless sensor networks and mobile devices.**

Following the essential stages required for multimedia communication, we categorize these techniques into two groups: multimedia compression techniques and multimedia transmission techniques. In the first group, we introduce the state-of-the-art compression algorithms and perform analyses and evaluations on energy efficiency in applying these compression algorithms to resource-constrained multimedia transmission systems. In the second group, we will further categorize the energy efficient transmission techniques into two sub-categories according to their different communication architectures. We review both cross-layer communication, including Unequal Error Protection (UEP), and independent-layer communication, focusing on Routing, MAC, and Physical layer protocols. We present the basic problem statement and objectives of these techniques, and survey multiple potential approaches that have been reported in the literature.

Our focus in this survey is to provide insight into different research directions to improve energy efficiency in wireless multimedia communication protocols for future developments.

***Index Terms*—Survey, Energy Efficiency, Multimedia, Compression, Communication, Mobile, Resource Constrained, Cross-Layer**

I. INTRODUCTION

WIRELESS multimedia communication has found a variety of applications in numerous different fields such as: traffic surveillance, battle field reconnaissance, security monitoring, health care, etc. Multimedia data, including audio, images and video is typically bandwidth intensive and delay-sensitive. These characteristics result in high demands on the communication and computing aspects of these systems, and thus a very high demand on energy resources. For most typical applications, the system architecture exhibits severe resource-constraints. Some of these constraints are a limited energy supply, low CPU speed, and limited memory for data storage. These constraints provide many challenges to provide desired application capabilities.

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The authors are with the Department of Computer and Electronics Engineering, University of Nebraska-Lincoln, USA (email: tma@unlnotes.unl.edu, mhempel@unlnotes.unl.edu, dpeng@unlnotes.unl.edu, hsharif@unlnotes.unl.edu).
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In wireless sensor networks, for example, resource constraint communication is a great challenge. Many research studies on providing an energy-efficient multimedia communication platform have been reported over the years. The basic idea of these energy-efficient techniques is to design and develop new communication methods that provide optimal performance under constrained resources. In this survey, we summarize these techniques and present insights into the state-of-the-art in research activities in this area.

A typical multimedia communication system consists of the following steps:

1) Multimedia Data Acquisition
2) Multimedia Compression and Processing
3) Multimedia Communication

We focus on two of these categories: compression techniques and communication techniques, as shown in Fig.1.

The first major group of energy efficient techniques in this area is compression. In todays mobile communication system, especially in embedded sensor networks, energy consumption is dominated by the wireless radio. For an example, the eZ430RF sensors radio, the CC2500 chipset [1], consumes about 28mA current in active mode, while its microprocessor, the MSP430 [2], consumes only 270A current in active mode. That represents a 100-fold difference. For example, in an experiment did conducted by Kenneth Barr [3], text files were compressed using the LZW by compression algorithm LZW and then were transmitted with 2.48mMbps for a savreduction in consumed energy by es about 50% energy than compared to transmitting raw text files without compression. Compression of the amount of data to be transmitted and thus keeping the radio in active state, is therefore vital in reducing the energy demand and thus have become an integral component of the multimedia communication system.

Existing compression algorithms were developed since the 1980s. In this survey, we will evaluate these compression algorithms from the perspective of suitability for use by energy-constrained multimedia communication systems. We also survey efforts to improve energy efficiency of these

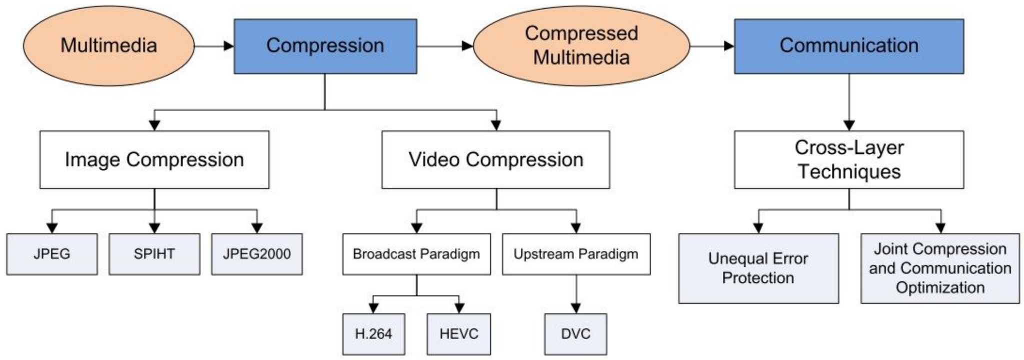

Fig. 1. A Summary of Energy Efficient Techniques for Multimedia Wireless Transmissions in Resource-Constrained Systems.

compression algorithms, provided for images and video, as since these are the most impactful for the energy efficiency.

In image compression, we introduce three major compression algorithms: JPEG, SPIHT and JPEG2000. An analysis of them in terms of computational demand, memory requirements, and compression efficiency is conducted in order to provide insight into the question of: *which one is the most suitable for energy-constrained systems?*

Additionally, related techniques on improving energy efficiency of these compression algorithms are also discussed. In video compression, we introduce H.264 and High-Efficiency Video Coding (HEVC). H.264 has been the state-of-the-art in video compression since its standardization in May 2003. HEVC is an emerging video coding standard designed for surpassing H.264 by providing two key approaches: 1) a low-complexity mode with significant improvements in execution time with marginal compression rate improvements over H.264, and 2) a high-complexity mode with much higher improvement of compression rates over H.264. HEVC is still in its development stage. The first draft of HEVC is expected to be complete in February 2012. Both H.264 and HEVC have the same core architecture: a complex encoder but simple decoder. This architecture makes them suitable for broadcast-based systems where the base station, serving many clients, is burdened by the complex encoder while each mobile client requires only a simple encoder.

By contrast we also present another popular video coding algorithm: Distributed Video Coding (DVC). Its architecture is different from previous two video coding algorithms in that it has a simple encoder but complex decoder. That makes it more applicable in to upstream transmissions such as a camera surveillance network where energy-constrained mobile camera sensors require a simple encoder while the base station can handle the high computational requirements of the decoder.

Related energy efficient techniques proposed for these three video algorithms are also summarized in this paper.

The second major focus of the energy efficient techniques is communication. Multimedia transmission has several unique characteristics: unequal importance, error tolerance, and error propagation. These characteristics set multimedia transmission apart from traditional data transmission.

In designing a cross-layer communication protocol suitable for multimedia, UEP was proposed. This strategy has been a key research topic since the 1990s. Many articles have been published on UEP. In this survey, we provide the basic problem statement covering all these efforts, and briefly summarize all solutions proposed in the literature. We provide insights on: 1) how well these solutions address this problem; and 2) the currently most effective solution. In addition, we survey one of the most important communication aspects in UEP, channel coding, and describe suitable channel codes proposed for multimedia.

In addition to UEP, another cross-layer communication approach called Joint Compression and Communication Optimization is also reviewed. This approach considers both compression and communication together to optimize the energy consumption for a given transmission quality, instead of only communication-matching found in the UEP approach.

The rest of this survey is organized as follows. Section II and Section III analyze energy efficiency of compression techniques for images and video, respectively. Section IV reviews two cross-layer techniques: Unequal Error Protection and Joint Compression and Communication Optimization. Section V gives the open areas in the future work. Finally, our concluding remarks are given in Section VI.

II. Energy-Efficient Image Compression

Digital images typically contain large redundancies. With todays compression techniques, a high-quality compressed image can usually occupy 1/8 the size of the original image. This is very favorable for energy savings in wireless communication since only a small portion of the image data needs to be transmitted. In this section, we compare existing image compression algorithms in terms of energy efficiency and compression efficiency, and give insights into their performance when these compression algorithms are applied to wireless communication systems. In addition, a survey of research efforts to improve energy efficiency in image compression is also presented.

Many image compression algorithms have been proposed in last 20 years. The basic idea of these algorithms is to reduce the high correlation in the image data so that any redundancy can be removed. Fig. 2 shows the basic concept of these algorithms.

In general, most current image compression algorithms can be categorized into Discrete Cosine Transform (DCT)-based

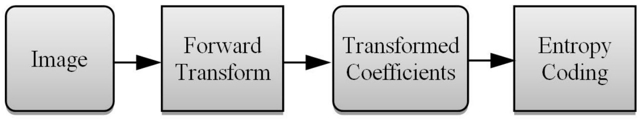

Fig. 2. Basic Compression Step.

compression and Discrete Wavelet Transform (DWT)-based compression.

A. DCT-based compression

JPEG compression is the most representative DCT-based compression algorithm. It is the most popular and widely used compression algorithm for images. In JPEG compression, the image source is first partitioned into blocks of 88 pixels and each block is coded independently [4]. After the Discrete Cosine Transform (DCT), each block of 64 DCT coefficients is uniformly quantized by a quantization table. After that, all of the quantized coefficients are ordered into a zigzag sequence, such that low-frequency coefficients are to be processed prior to high-frequency coefficients.

The DCT transform is very fast. Furthermore, the independent nature of the 88 block mechanism results in very low memory requirements for the JPEG algorithm. Therefore, the whole compression system is very fast and energy-efficient. The drawback of JPEG is the low compression quality. Despite that, it is still the most widely used compression in commercial products. JPEG consists of a large number of additions and multiplications involving real numbers. In processor architectures operations using float data types are expensive and energy consuming by comparison. Most hardware platforms, instead of having dedicated floating point hardware units, rely on simple and low-cost fixed-point arithmetic units to emulate floating-point operations. However, emulating floating point operations is slow and energy-inefficient. According to current studies, the precision of floating-point operations is often far greater than is necessary in light of quantization process in JPEG [5]. Some research efforts utilize this effect to improve computational energy efficiency. Table 1 provides an overview of such efforts and their results.

In Table 1, the floating point code and the fast INT (integer) code are from the Independent JPEG Group (IJG) library [6]. Adaptive INT codecs are from paper [5]. The quantization table is selected as JPEGs Table 50. As the results show, the floating point implementation has the highest computational load, but it has the same compression quality as the Slow INT codec. This fact demonstrates the floating point algorithm is unnecessarily precise due to subsequent quantization. The Fast INT and Slow INT codec from IJG use constant bit-width integers to emulate the floating point operation. They have capabilities to adapt to changing image quality requirements, however. In Adaptive INT [5], compression computation range and precision are analyzed in advance. First, the required integer bit-width to completely represent the signal is computed. Second, the precision analysis is conducted with the given quality requirement and the minimal required precision in terms of the fractional bit-width. Finally, according to calculated integer bit-width and fractional bit-width, the most energy efficient compression code requiring minimal CPU cycles is selected. Thus, computational energy consumption is significantly reduced compared to constant bit-width integer calculations.

TABLE I
COMPUTATION COST COMPARISON OF JPEG IMPLEMENTATIONS.

Methods	Executing Time	Energy	PSNR (Goldhill)
Float Point (IJG)	103.12	2268.60	27.0
Slow INT (IJG)	6.05	133.15	23.8
Adaptive INT(slow)	4.80	105.50	26.1
Fast INT(IJG)	3.25	71.40	27.0
Adaptive INT(fast)	1.39	30.67	27.0

B. DWT-based compression

Discrete Cosine Wavelet (DWT) is a very powerful transform that provides significantly higher compression efficiency than DCT at higher compression ratio. However, DWT is also more complex and computationally intensive than DCT. Thus, several research activities focus on reducing complexity and required memory. Among them, the lifting scheme [7-8] is one of the best algorithms to calculate the wavelet transform in an energy efficient manner. Compared to a convolution filter, the lifting scheme uses fewer filter coefficients; therefore it provides a faster implementation of DWT. Lifting wavelet also provides memory reduction through in-place computation of wavelet coefficients.

In order to further reduce energy consumption in wavelet transform, papers such as [9-10] propose an approach of skipping the computation for the coefficients in high-pass filters in the wavelet transform. Their technique is inspired by the observation that high-pass filter output coefficients are of very low value, typically. According to their studies in image lena 512x512 80% of the high-pass coefficients for wavelet transform level 1 octave are less than 5, claiming that setting the high-pass coefficients to zero has minimal quality impact. By skipping the high pass filter coefficient computation, they can trade-off the reconstruction quality with computational energy consumption. Their experimental results show that 90% of energy savings can be achieved over adaptive wavelet image compression at a low PSNR of 25db.

In DWT-based compression, the two best-known compression algorithms are “Set Partitioning in Hierarchical Trees” (SPIHT) and JPEG2000.

In SPIHT, an image is first transformed into the wavelet domain where the quad-tree structure is explored by a bit-plane coding algorithm. The inter-band wavelet correlation is reduced by two pass filters: the sorting pass and the refinement pass. The output of these two filters is a bit-stream with descending importance order.

This compression is very fast and has high compression quality. In addition, many improvements have been made by many researchers over the traditional SPIHT image compression algorithm. In the SPIHT algorithm three lists are used to temporarily store the images quad-tree structure and significance information. This requires a large amount of memory and causes hardware implementation difficulties.

Listless Zerotree Coding (LZC) [11] is proposed to overcome this drawback of SPIHT. LZC uses two flag maps to store coding information instead of three sets in SPIHT, which greatly reduces memory requirements. However, LZC uses the depth-first searching strategy which lowers compression performance of the codec. Subsequently, this compression quality compromise problem was addressed in [12-13].

A recent paper [14] proposed an improved version of the SPIHT codec which surpassed the performance of traditional SPIHT without adding any overhead. In their codec, the PSNR is improved by 0.2 to 0.4dB over a broad compression rate range. That makes SPIHT without arithmetic coding competitive even with JPEG2000. Because of all these efforts, SPHIT has become one of the best choices for energy-efficient compression algorithms.

JPEG2000 is another well-know DWT based compression algorithm. In JPEG2000, an image is divided into tiles and each tile is transformed independently. After that, the subbands of the tile are divided into packet partition locations. Finally, each packet partition location is divided into code-blocks.

JPEG2000 adopts the Embedded Block Coding with Optimal Truncation (EBCOT) image compression technique [15]. In EBCOT, information coding and information ordering are separated. It is referred to as two-tier coding. In tier 1, each of these code blocks carries out a context-dependent, binary arithmetic coding of bit-planes [16]. An embedded bit stream is then generated for every code block. However, since the subbands are partitioned and are encoded independently, intra-subband redundancy is explored instead of inter-subbands in SPIHT. The tier-2 coder operates on the compressed information of every block to arrange their contributions in each quality layer, in a process referred to as packetization [17]. At the end of the tier-2 process, a compressed bit stream is obtained and ready for transmission.

JPEG2000 includes comprehensive optimizations and features. The quantization step size can be adjusted by the rate-control mechanism. Also each code block bit stream is truncated in an optimal way to minimize distortion due to bit-rate constraints. The features of JPEG2000 include SNR scalability, resolution scalability as well as random access.

JPEG2000 compression provides slightly higher compression quality than SPIHT. However, its multi-layer coding procedure is very complex and computationally intensive. Also, the optimization processes such as optimal truncation as well as resolution features greatly add to the computational requirements. The demand for multiple coding tables for arithmetic coding requires extra memory allocation which makes hardware implementations of the coder more complex and expensive.

Based on our extensive studies on these three famous compression algorithms, we list their strengths in terms of memory requirement, compression quality, coding speed and computational load in Table II. These findings are corroborated in [18].

Given the above information, we can conclude that SPIHT currently is the most energy-efficient and applicable compression algorithm for image-based wireless communication systems, since it provides a high compression ratio with relatively low complexity. JPEG2000 is typically too complex to apply in wireless sensor networks due to the sensor nodes limited computational ability. JPEG is not as energy efficient as SPIHT, but is a reasonable alternative when the image transmission quality requirement is not very high.

TABLE II
COMPUTATION COST COMPARISON OF COMPRESSION ALGORITHMS.

Methods	JPEG	SPIHT	JPEG2000
Forward Transform	DCT	DWT	DWT
Computation Load	low	low	high
Memory Reuquirement	low	low	high
Coding Speed	high	high	average
Compression Quality	low	high	high

JPEG2000 is a well-established image compression algorithm. Significant research efforts have been conducted in improving its compression efficiency. However, reducing the complexity and computational overhead of JPEG2000 is still an open research area.

III. Energy Efficient Video Compression

Video is another very important type of multimedia. It, however, generates a large amount of data for transmission and processing, and storage, as well as exhibits high bandwidth transmission requirements. Thus, it is a challenging task to transmit video in resource-constrained systems. Compression is obviously a major required step before transmission since it eliminates a large amount of data from having to be transmitted. In this section, the state-of-the-art in video coding algorithms is investigated. Energy efficiency strengths of these video coding algorithms are analyzed for different application scenarios.

A. H.264

For the last two decades, standardization efforts in MPEG and ITU-T have played a key role for traditional broadcasting paradigms in wireless video communication. Subsequently, the H.264/Advanced Video Coding (AVC) standard, completed in May 2003, represents the most efficient video codec available to date. In traditional broadcast architectures, the most computational complexity is concentrated at the encoder, while the decoder is significantly less complex and thus exhibits far lower processing requirements. For typical implementations, the encoder is 5-10 times more complex than the decoder [19].

In H.264, the encoder includes processes of rate-distortion optimized motion estimation (ME) and mode decision. These processes are very complex and energy consuming. Thus, most research efforts in saving energy in H.264 compression are focused on these two processes. The methods can be categorized into two groups: encoding procedure simplification and complexity reduction in mode prediction.

1) Encoding procedure simplification: H.264 is a highly complex compression approach. For example, the intra-prediction for 4x4 luminance blocks has to compute nine different prediction modes to obtain the best prediction performance. To simplify this process, Wang et al. [20] developed a fast algorithm by using the property of linear transform and the fixed-spatial relationship of predicted pixels in each intra mode. About 50% computational burden can be reduced by using the fast Sum of Absolute Transformed Differences (SATD) algorithm without a degradation in video quality. Furthermore, they propose a two-stage simplified SATD method in which the Sum of Absolute Transform (SAD) criterion is used to eliminate unwanted modes before fast SATD computation. Their experimental results demonstrate that about 70% computational cost can be saved with negligible PSNR loss for H.264 intra prediction.

Andersen et al. [21] present a simple operational method that can trade-off between rate-distortion and complexity. The complexity is measured by the number of visited search positions weighted by the size of each block type. This operational method provides a general framework for real-time implementation of H.264 encoders in computationally constrained platforms. Results show a speed-up by a factor of 4 is achievable at only 1% increase in rate.

2) Reducing complexity in mode prediction: Hsia et al. [22] propose a fast intra prediction mode decision algorithm for 4x4 intra blocks. This algorithm reduces the computational complexity of the 4x4 block intra-prediction based on partial sampling prediction and symmetry of adjacent angle modes. Experimental results show that the proposed algorithm can reduce computation time of intra prediction by more than 60% while maintaining similar video quality and bit rate.

Kannangara et al. [23] present a complexity reduction algorithm for H.264 encoders. The likely to be skipped macroblocks (MBs) are identified before motion estimation. Hence, the further computational processing of these MBs is also saved. Their new algorithm is based on a well-known rate-distortion optimization method and enables an H.264 encoder to decide whether to encode or to skip each MB. They claim that their algorithm can achieve computational savings of 19%-67% with no significant loss of rate-distortion performance.

Crecos et al. [24] show that the accurate detection of the skip mode type without performing the computationally intensive mode decision is highly desirable for computational speed-ups. By using a low-impact set of smoothness constraints and neighborhood information as well as a set of skip mode conditions, they propose an inter-mode decision scheme for P slices in the H.264 video coding standard. They achieve 35%-58% reduction in run time and a 33%-55% reduction in CPU cycles for both the rate-controlled and the non-rate-controlled versions of H.264.

Based on the analysis in paper [25], the entire computation for mode selection can be reduced significantly if skipping calculation for less probable modes. In their work, an algorithm for fast coding mode selection in H.264/AVC encoders is proposed. Extensive experiments show that the proposed methods can reduce execution time of mode selection in H.264/AVC by 85% on average while the average PSNR loss is only 0.07dB.

Kim et al. [26] propose a fast inter-mode determination algorithm on the basis of the rate-distortion cost of the tracked MB for the current MB. They verify the performance of the proposed scheme through comparative analysis of experimental results using JM reference software. An improvement of 40%-70% with an average loss of 0.052dB and bit increment of 0.7%-0.8% is achieved.

B. Distributed Video Coding

Unfortunately, H.264 is not suitable for upstream video applications, such as low-power multimedia sensor networks and wireless video surveillance cameras, because these applications require simple encoders instead of simple decoders. In these upstream applications, lightweight encoding with high compression efficiency is needed. Wyner and Ziv [27] established an information theory for lossy coding, which claims efficient compression can be achieved by leveraging knowledge of the source statistics at the decoder only. Based on this theory, a new coding concept called Distributed Video Coding (DVC) was presented. Different from traditional coding, DVC relies on a new statistical framework instead of the deterministic approach of conventional coding techniques. It changes the traditional codec to a simple encoder and complex decoder architecture. Following this direction, the seminal DVC schemes have been proposed in [28-29], followed by a large amount of related publications such [30-31]. In this survey, we only focus on the low complexity and energy saving aspects of DVC. To our knowledge, few publications are reported in this area.

Areia et al. [32] propose a hybrid rate control solution to reduce the high WZ decoding complexity for Stanford architecture under constraints of 1) the added complexity at encoder is negligible; 2) the overall rate-distortion is negligible. Their results show that coding complexity reductions of up to 70 % may be possible for more complex sequences.

Belief Propagation (BP) is one of the most significant approximate algorithms available for decoders. It helps gather information from neighborhoods of each pixel in an image to find the minimum matching cost of local points and their neighborhoods. Paper [33] examines the parallelisms in the BP method for stereo vision on multi-core processors. Their results show their BP method can achieve a 13.5-times speedup compared to single-processor implementations.

Papers [34] and [35] propose a shuffled belief propagation decoder of low-density parity-check codes (LDPC). Their results show that 10 iterations of the proposed approach with four sub-decoders achieve the same performance as 70 iterations of the standard BP decoder.

C. Emerging HEVC standard

In January 2010, ISO-IEC/MPEG and ITU-T/VCEG reached an agreement to form the joint collaborative team on video coding (JCT-VC) to develop a next-generation codec: High Efficiency Video Coding (HEVC) [36]. HEVC aims to develop: 1) a low-complexity mode with significant improvements in execution time with marginal compression rate improvements over H.264, and 2) a high-complexity mode with much higher improvement of compression rates over H.264. The initial draft is expected to be released in February 2012. Although HEVC is still under development, there are some subjective results [37, 35] already showing that it achieves similar visual quality to H.264/AVC with around 30% bit rate reduction for low-delay applications, and with around 20% bit rate reduction for random access experiments on average, but with lower complexity than the H.264/AVC baseline profile. Currently, HEVC is expected to surpass H.264 in terms of energy efficiency at low complexity operation.

In summary we can claim that:

1) The current H.264 standard is well-suited for downstream broadcast communication where decoders in mobile terminals are simple while the central encoders exhibit the highest complexity burden
2) DVC is highly preferred in multimedia sensor networks and surveillance camera system for its capability of reversing the complexity burden between encoder and decoder.
3) The currently under development HEVC standard is expected to provide substantial improvements in coding efficiency over H.264.

IV. Cross-Layer Techniques for Multimedia Communication

In this section, we focus on two well-known techniques for wireless multimedia communication: Unequal Error Protection (UEP) and Joint Compression and Communication Optimization. The basic idea of UEP is to apply unequal communication protection to different parts of the compressed multimedia data in order to maximize the performance of the overall multimedia communication. In UEP technique, we provide the idea and theoretical problem statement of this technique. We then survey the state-of-the-art solutions for this problem. Thirdly, we also summarize the channel code design for this problem presented in the current literature. Also we describe the idea behind joint compression and communication optimization in this section.

A. UEP Optimization Problem

Due to the fact that multimedia information contains significant amounts of redundancy, to efficiently utilize limited resources data compression is a necessity. Compared with general data, however, compressed multimedia information has three distinct characteristics.

1) **Unequal Importance**: Different parts of the compressed data hold different importance for perceptually and structurally reconstructing the original data during decompression.
2) **Error Tolerance**: Multimedia data can be recovered with some tolerable degradation even though errors exist.
3) **Error Propagation**: If some bits are corrupted, the bits which depend on them become useless.

Papers [39-40] have extensively looked into these unequal importance properties of compressed multimedia. The studies show that distortion reduction increases nonlinearly as the bitplane count increases. These studies suggest that a potential performance gain can be achieved when the UEP communication technique is applied accordingly.

This problem is often regarded as a UEP optimization problem. Over the past 10 years, many research activities have been reported in this area. Lu et al. [41] present an efficient video transmission approach which minimizes energy consumption under expected video quality constraints by jointly selecting scalable enhancement layers, channel transmission rate adaptation and forward error correction (FEC) error protection. Their experiment shows 5% to 30% energy can be saved while achieving the expected video distortion. Wei et al. [42] propose an energy-efficient JPEG2000 image transmission system over point-to-point wireless sensor networks. In their work, energy consumption is saved by jointly adjusting source coding schemes, channel coding rates, and transmitter power levels in an optimal way. An investigation of the use of an energy-constrained cross-layer approach for the transmission of progressively coded images over packet-based wireless channels is presented in [43]. An optimum power allocation algorithm is designed to enable unequal error protection of a pre-encoded image. Their experimental results demonstrate that it is possible to achieve a relevant performance enhancement with the proposed approach over uniform error protection. In addition, by jointly considering source coding, error concealment, and transmission power management at the physical layer, Wang et al. [44] propose an unequal error protection for the shape and texture information that minimizes the expected distortion at the receiver, given energy and delay constraints. Experimental results of their work indicate that the proposed unequal error protection scheme significantly outperforms the equal error protection method. To sum up, the key idea of all these works is to match communication strategies to the characteristic of the compressed multimedia by the UEP technique in order to optimize overall performance of multimedia communication.

The problem statement of this technique can thus be summarized as: 1) Given a distortion constraint, to minimize the energy consumption. 2) Given an energy consumption constraint, to minimize distortion. These two problems are actually the same problem in terms of the mathematical solution. For simplicitys sake, we do not distinguish them in this paper, and only formulate the first problems solution since it equally applies to the second problem statement as well.

The first problem statement can be presented as follows: Assume that the compressed multimedia information has N layers. Let S_i denote a particular communication strategy, with parameters such as coding algorithms, transmit powers, etc., applying in the layer i of the multimedia data. Let D_0 denote the overall distortion when no layer is received by the decoder.$\overline{G}_{S_i}$ is the expected gain (distortion reduction) when the layer i is protected by strategy S_i. Assume the distortion metric is additive, then the overall expected gain can be calculated as

$$\overline{G}_S = \sum_{i=1}^{N} \overline{G}_{S_i}, \tag{1}$$

The expected distortion is

$$\overline{D}_S = D_0 - \overline{G}_S, \tag{2}$$

Energy consumption is the sum of energy consumption of every layer.

$$\overline{E}_S = \sum_{i=1}^{N} \overline{E}_{S_i}, \tag{3}$$

The problem then can be formulated as a constrained discrete optimization problem

$$arg \min_{S} : \overline{E}_S \quad s.t. \quad D_S < D_{max} \tag{4}$$

Finding an optimal solution to the above optimization problem is difficult because deriving analytical expressions for distortion and energy consumption as functions of communication strategies is very challenging, since these functions are nondeterministic (only worst case or average values can be determined) and nonlinear.

B. Solutions

Several optimization algorithms have been proposed to solve this problem. However, the dominant solution for this problem is dynamic programming.

1) Dynamic Programming: The first and seminal dynamic programming solution is proposed by Chande et al [47]. In their work, two solution-space constraint optimization problems and their solutions were presented within the framework of dynamic programming: 1) the distortion-based optimal unequal protection, 2) the rate-based optimal unequal protection . Their dynamic solutions have the complexity of $O(N^2)$ and $O(N)$ for these two problems, respectively. N is the number of transmitted packets.

Later on, Stankovic et al. [48] found a fast linear-complexity algorithm to maximize the expected error-free source rate. Hamzaoui et al claim that the distortion-optimization problem can be solved with a local search starting from the rate-optimal solution [49, 50]. Thus, they combine the rate-optimal solution in [46, 47] with a local search algorithm to solve the distortion-optimization problem. This way, the complexity is reduced to a linear complexity. To the best of our knowledge, it is one of the fastest algorithms known so far for this problem.

Another fast algorithm is reported in paper [51]. In their work, a method to find an unequal error protection scheme for progressively encoded image data based on dichotomic search is presented. Their results have shown that this optimization method achieves an average quality that is virtually equivalent to that obtained by the linear search method.

2) Other Solution:

a) Discrete Ergodic Search: Because the solution of the optimization problem is discrete and limited, some simple cases exhibit a small search space for possible strategies S. Therefore, discrete ergodic search would be very direct, accurate and simple. One solution proposed by paper [42] uses the convex concept to find the optimal point in each layer. Only the optimal points whose distortion constraints are satisfied are collected. Complexity of the discrete ergodic search is directly proportional to $O(N \times L)$, where L is the number of strategies and N is the number of layers. In paper [40], the number of strategies is only three. In this case, the discrete ergodic search is also adopted as their solution.

b) Theoretical Solution: Some researchers are trying to find a closed form expression for this optimization problem. For instance, a closed mathematical expression for the optimal power allocation with various packets is formulated in paper [43]. However, their mathematical closed-form expression is heavily dependent on the theoretical model they assume. These theoretical models are usually too simplistic to be accurate in practice. In their solution, an erasure channel is assumed, and they only consider the slow fading channel with additive white Gaussian noise, which rarely is applicable. Still, their work represents an improvement of UEP performance and provides insight into potential future research in this direction.

To sum up, the theoretical solution approach is typically very fast but is typically not applicable to practical use. Discrete ergodic search is simple to implement and is suitable for limited search spaces only. For the large search spaces in selecting a potential strategy S, especially for complex video transmissions, this problem quickly becomes very computationally intensive. Dynamic programming therefore is the best choice in this case. Despite all these research efforts, the optimization problem for UEP is still a challenging and difficult problem and will continue to attract the attention of researchers.

C. Channel Codes for Cross-Layer Optimization

The other important research issue in the cross-layer optimization problem is channel code design. The basic idea of this optimization problem is to match communication strategies to the multimedia datas structure. Channel codes which provide a wide selection of error protection capability thus become a key aspect of this matching problem. In past decades, many channel codes have been proposed in the literature.

Among them are rate-compatible codes (RC), where the parity bits for higher-rate codes are embedded in those of lower-rate codes and all codes in the sequence can be encoded and decoded using a single encoder/decoder pair. This is a very attractive and widely used channel code.

One of the more important RC codes is the Rate-Compatible Punctured Convolutional (RCPC) code which is a simple and easy to construct UEP code for different parts of an embedded code stream. It is among the most widely applied codes for this cross-layer optimization problem [52-55].

The other important RC code is the Rate-Compatible Punctured Turbo Code. The Punctured Turbo Code [56] provides stronger error protection than the RCPC code. However, the block size of turbo codes is typically larger than that of the RCPC code. Related reports can be found in paper [57].

Rate-Compatible Low-Density Parity Check (RCLDPC) code is another popular channel code used in this optimization problem [58-60]. It has some advantages over RCPC code, namely 1) it is parallelizable and can be realized at much faster speed than the turbo decoder and 2) almost all the errors are detectable. It also shows better performance than the RCTC code. However, the complexity is still the primary weakness of this code.

To sum up, RCPC is the simplest and fastest channel code amongst them. Other channel codes such as RCTC and

RCLDPC give better performance while suffering additional computational overhead and are thus not widely used for multimedia transmissions in resource-constrained environments.

D. Joint Compression and Communication Optimization

UEP matches the communication strategy to the source coding but does not consider the power consumption as a result of the source coding itself. As a result, researchers proposed a different approach to cross-layer optimization called Joint Compression and Communication Optimization. In this approach, compression power consumption and transmission power consumption are jointly considered in order to optimize the performance of the entire transmission system. This approach is mainly applied to video transmission systems, since the video coding itself also exhibits a high power consumption compared with the wireless transmission. This approach aims to find the optimal trade-off between compression and transmission in order to achieve an overall better transmission quality. Below we reviewe some specific research publications related to this approach.

Lu et al. in [61] formulated the power consumption of the H.264 codec as a function of INTRA rate, encoding rate, and transmission power consumption as a function of encoding rate, channel coding rate, and radiated energy per transmitted bit. They conclude that when channel conditions are good, source coding consumes significantly more power than transmission. Source coding therefore is required to be simplified for less computational overhead at the expense of transmitting more data with more transmission overhead. On the other hand, when the channel conditions are deteriorating more complex source coding using the H.264 codec is required to achieve a better balance to the high transmission energy requirement.

Lu et al. in [62] then proposed an approach for minimizing the total power consumption of a mobile transmitter given the fixed end-to-end source distortion. In that approach, the H.264 encoder power consumption model and RS channel coding power consumption model are formulated. By using these power consumption models, they successfully optimized the total power consumption of the transmitter.

In [63], He et al. extended the traditional rate-distortion (R-D) optimization approach to power-rate-distortion (P-R-D) optimization by exploring the encoding power consumption model. They analyzed the encoding mechanisms of typical video coding systems, and developed a parametric video encoding architecture. Also, by using dynamic voltage scaling the complexity scalability is able to be translated into energy consumption of the video encoder. By using this approach they successfully established an analytical P-R-D model and the power consumption is generically optimized using that method.

Wang et al. in [64] proposed an optimization approach to minimize the sum of compression powers and transmission powers of all users, subject to the received video quality at each terminal in a multiple-terminal video transmitting environment. Thus, they extended previous research to multiple terminal users, globally optimizing the entire networks power consumption.

To summarize, the joint compression and communication optimizations strategy is to balance the resources allocated to compression and communication in order to optimize the energy consumption, and is driven by the desired end-to-end link quality. This approach is more generic and complex than the UEP approach. However, the solution of UEP can be integrated into this approach as well. Additional publications in this area can be found in [65-71].

V. Future Work and Open Issues

Compression efficiency of image compression algorithm design is a well-studied area. However, determining low-complexity efficient compression algorithms suitable for resource-constrained communication systems is still an open area. Especially the problem of how to reduce the complexity of JPEG2000 such that the compression energy can be saved in the communication system is challenging but a very rewarding open research area.

One promising video codec, HEVC, is expected to provide substantial improvements in coding efficiency over H.264. How to trade off the power consumption of HEVC against wireless transmission power consumption will very likely become the next cross-layer design research focus in wireless communication systems.

Energy-efficient cross layer design is a very complex problem and requires to systematically and effectively research all the network layer optimizations jointly [72].

VI. Conclusion

In this paper, we conducted a comprehensive survey for existing energy-efficient techniques for multimedia communication in resource-constrained systems. We introduced two groups of energy-efficient techniques in two integral multimedia communication phases: energy-efficient multimedia compression and energy-efficient multimedia transmission. In the first group, existing multimedia compression algorithms are evaluated and compared to present an insight into the potential for energy efficiency for these compression algorithms. In the second group, important transmission techniques cross-layer communication technique is reviewed. The summary of these transmission techniques aims to provide a vision of the current stage of research in energy-efficiency for transmission systems. This survey presents opportunities to identify future research directions and serve as a foundation for related research efforts.

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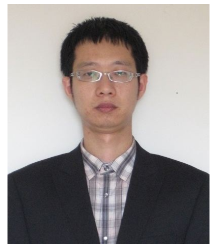

Tao Ma received the B.Sc. and M.Sc. degrees from Xian Jiaotong University, China, in 2005 and 2008 respectively, both in electrical engineering. He is currently pursuing the Ph.D. degree and in Department of Computer and Electronics Engineering, University of Nebraska-Lincoln. His research areas are Cross-layer design for QoS provisioning in wireless data networks, and multi-media distribution, ultra-low power sensor network.

Michael Hempel received the Ph.D. degree in computer engineering from the University of Nebraska-Lincoln in 2007. He is currently a Research Assistant Professor in the Department of Computer and Electronics Engineering, University of Nebraska-Lincoln. His research interests include wireless communications networks and multimedia communications.

Dongming Peng received the B.A. and M.A. degrees in electrical engineering from Beijing University of Aeronautics and Astronautics, Beijing, China, in 1993 and 1996, respectively, and the Ph.D. degree in computer engineering from Texas A&M University, College Station, in 2003. From 1996 to 1997, he was a faculty member at Beijing University. In 2002, he joined the University of Nebraska-Lincoln, where he is currently an Associate Professor. His research interests include digital image processing, computer architectures, parallel and distributed computing, and sensor network. Dr. Peng is one of the recipients of the Best Paper Award in IEEE WCNC 2008. He has also served as a referee and program committee member for several conferences and journals.

Hamid Sharif is the Charles J. Vranek Professor in the Department of Computer and Electronics Engineering at the University of Nebraska-Lincoln. He received his BSEE from University of Iowa, MSEE from University of Missouri-Columbia, and PhD from University of Nebraska-Lincoln. He is the director of Advanced Telecommunications Engineering Laboratory (TEL) at University of Nebraska. Professor Sharif has published over 200 research articles in international journals and conferences and has been the recipient of a number of best papers. Dr. Sharif has been serving on many IEEE and other international journal editorial boards and currently is the co-editor-in-chief for the Wiley Journal of Security and Communication Networks. He has contributed to the IEEE in many roles including the elected Chair of the Nebraska Section, elected Chair of the Nebraska Computer Chapter, elected Chair of the Nebraska Communication Chapter, and the Chapter Coordinator for the IEEE Region 4 in US.