Middle-East Journal of Scientific Research 19 (10): 1307-1312, 2014
ISSN 1990-9233

DOI: 10.5829/idosi.mejsr.2014.19.10.11244

Compressed-Sensing-Enabled Video Streaming for Wireless Multimedia Sensor Networks

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Abstract: In this paper presents the design of a networked system for joint compression, rate control and error correction of video over resource-constrained embedded devices based on the theory of compressed sensing. The objective of this work is to design a cross-layer system that jointly controls the video encoding rate, the transmission rate and the channel coding rate to maximize the received video quality. First, compressed sensing based video encoding for transmission over wireless multimedia sensor networks (WMSNs) is studied. It is shown that compressed sensing can overcome many of the current problems of video over WMSNs, primarily encoder complexity and low resiliency to channel errors. A rate controller is then developed with the objective of maintaining fairness among video streams while maximizing the received video quality. It is shown that the rate of compressed sensed video can be predictably controlled by varying only the compressed sensing sampling rate. It is then shown that the developed rate controller can be interpreted as the iterative solution to a convex optimization problem representing the optimization of the rate allocation across the network. The error resiliency properties of compressed sensed images and videos are then studied and an optimal error detection and correction scheme is presented for video transmission over lossy channels.Finally, the entire system is evaluated through simulation and testbed evaluation. The rate controller is shown to outperform existing TCP-friendly rate control schemes in terms of both fairness and received video quality. Testbed results also show that the rates converge to stable values in real channels.

Key words: Compressed Sensing · Network Optimization · Multimedia Streaming · Congestion Control · Sensor Networks

INTRODUCTION

Wireless Multimedia Sensor Networks (WMSN) are self-organizing systems of embedded devices deployed to retrieve, distributively process in real-time, store, correlate and fuse multimedia streams originated from heterogeneous sources [1]. WMSNs are enablers for new applications including video surveillance, storage and subsequent retrieval of potentially relevant activities and person locator services. In recent years, there has been intense research and considerable progress in solving numerous wireless sensor networking challenges. However, the key problem of enabling real-time quality-aware video streaming in large-scale multihop wireless networks of embedded devices is still open and largely unexplored. There are two key shortcomings in systems based on sending predictively encoded video (e.g. MPEG-4) Encoder Complexity [2]. Predictive encoding requires complex processing algorithms, which lead to high energy consumption. New video encoding paradigms are therefore needed to reverse the traditional balance of complex encoder and simple decoder, which is unsuited for embedded video sensors [3]. Recently developed distributed video coding algorithms exploit the source statistics at the decoder, thus shifting the complexity to the decoder. While promising most practical Wyner-Ziv codecs require end-to-end feedback from the decoder which introduces additional overhead and delay. Furthermore, gains demonstrated by practical distributed video codecs are limited to 2-5 dBs PSNR. Distributed video encoders that do not require end-to-end feedback have been recently proposed but at the expense of a further reduction in performance [4]. In addition, all of these techniques require that the encoder has access to the entire video frame (or even multiple frames) before encoding the video. Limited Resiliency to Channel Errors.

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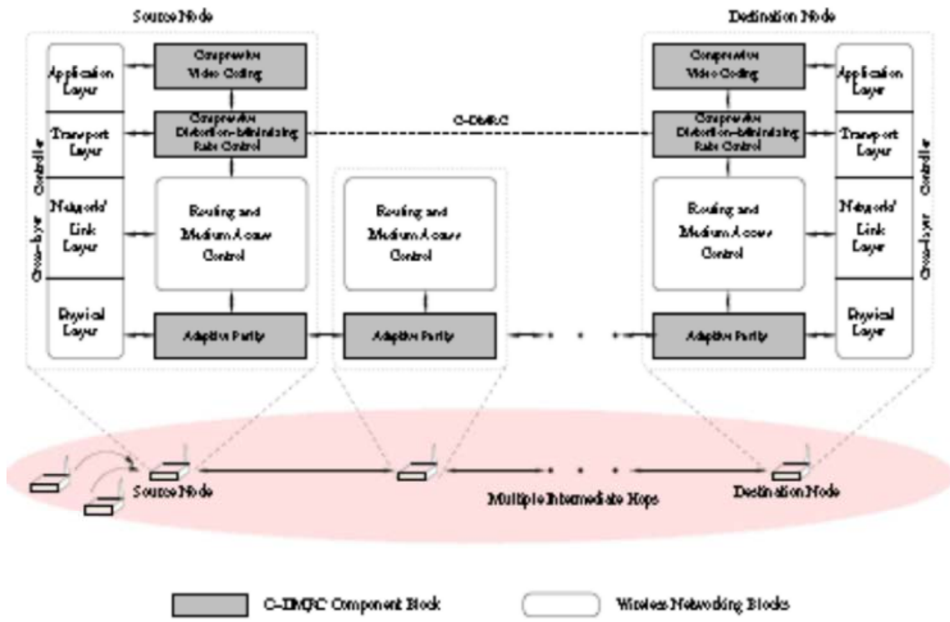

Fig. 1: Arohiectme of C-DMRC System

In existing layered protocol stacks based on the IEEE 802.11 and 802.15.4 standards, frames are split into multiple packets [5]. If even a single bit is flipped due to channel errors, after a cyclic redundancy check, the entire packet is dropped at a final or intermediate receiver. This can cause the video decoder to be unable to decode an independently coded (I) frame, thus leading to loss of the entire sequence of video frames. Instead, ideally, when one bit is in error, the effect on the reconstructed video should be unperceivable, with minimal overhead. In addition, the perceived video quality should gracefully and proportionally degrade with decreasing channel quality [6].

In this paper, we show that a new cross-layer optimized wireless system based on the recently proposed compressed sensing (CS) paradigm can offer a promising solution to the aforementioned problems. Compressed sensing (aka “compressive sampling”) is a new paradigm that allows the faithful recovery of signals from $M << N$ measurements, where N is the number of samples required for the Nyquist sampling. Hence, CS can offer an alternative to traditional video encoders by enabling imaging systems that sense and compress data simultaneously at very low computational complexity for the encoder. Image coding and decoding based on CS has recently been explored [7]. So-called single-pixel cameras that can operate efficiently across a much broader spectral range (including infrared) than conventional silicon-based cameras have also been proposed. However, transmission of CS images and video streaming in wireless networks and their statistical traffic characterization, are substantially unexplored.

For this reason, we introduce the Compressive Distortion Minimizing Rate Control (C-DMRC), a new distributed crosslayer control algorithm that jointly regulates the CS sampling rate, the data rate injected in the network and the rate of a simple parity-based channel encoder to maximize the received video quality over a multi-hop wireless network with lossy links. The cross-layer architecture of our proposed integrated congestion control and video transmission scheme is shown in Fig. 1. By jointly controlling the compressive video coding at the application layer, the rate at the transport layer and the adaptive parity at the physical layer, we leverage information at all three layers to develop an integrated congestion-avoiding and distortion-minimizing system [8]. Our work makes the following contributions:

- Video Transmission Using Compressed Sensing. We develop a video encoder based on compressed sensing. We show that, by using the difference between the CS samples of two frames, we can capture and compress the frames based on the temporal correlation at low complexity without using motion vectors [9].

- Distortion-based Rate Control. C-DMRC leverages the estimated received video quality as the basis of the rate control decision. The transmitting node controls the quality of the transmitted video directly. Since the data rate of the video is linearly dependent on the video quality, this effectively controls the data rate. By controlling congestion in this way, short-term fairness in the quality of the received videos is maintained even over videos that have very different compression ratios [10].
- Rate Change Aggressiveness Based on Video Quality. With the proposed controller, nodes adapt the rate of change of their transmitted video quality based on an estimate of the impact that a change in the transmission rate will have on the received video quality. The rate controller uses the information about the estimated received video quality directly in the rate control decision. If the sending node estimates that the received video quality is high and round trip time measurements indicate that current network congestion condition would allow a rate increase, the node will increase the rate less aggressively than a node estimating lower video quality and the same round trip time. Conversely, if a node is sending lowquality video, it will gracefully decrease its data rate, even if the RT T indicates a congested network. This is obtained by basing the rate control decision on the marginal distortion factor, i.e. a measure of the effect of a rate change on video distortion.
- Optimality of Rate Control Algorithm.We finally show that the proposed rate control algorithm can be interpreted as an iterative solution to the optimal rate allocation problem (i.e. finding the rates that maximize the sum of video qualities).The remainder of this paper is structured as follows. In Section II, we discuss related work. In Section III we introduce the C-DMRC system architecture. In Section IV, we describe the proposed video encoder based on compressed sensing (CSV). In Section V, we introduce the rate control system [11].

Section VI discusses channel coding issues. The performance results are presented in Section VII. In Section VIII, we show how the proposed rate control subsystem can be interpreted as the solution algorithm to a rate optimization problem. Finally, in Section IX we draw the main conclusions and discuss future work.

Related Work: The most common rate control scheme is the well-known transmission control protocol (TCP) [12]. Because of the additive increase/multiplicative-decrease algorithm used in TCP, the variation in the rate determined by TCP can be very distracting for an end user, resulting in poor end user perception of the video quality. In addition, TCP assumes that the main cause of packet loss is congestion and thus misinterprets losses caused by channel errors as signs of congestion. These considerations have led to a number of equation-based rate control schemes, which analytically regulate the transmission rate of a node based on measured parameters such as the number of lost packets and the round trip time (RT T) of the data packets. Two examples of this are the TCP-Friendly Rate Control, which uses the throughput equation of TCP Reno and the Analytical Rate Control (ARC) [13]. Both of these schemes attempt to determine a source rate that is fair to TCP streams. However, in a WMSN, priority must be given to the delay-sensitive flows at the expense of other delay-tolerant data. Therefore, both TCP and ARC result in a transmission rate that is more conservative than the optimal rate. For this reason, in an effort to optimize resource utilization in resource-constrained WMSNs, our scheme does not take TCP fairness into account. Recent work has investigated the effects of packet loss and compression on video quality. In the authors analyze the video distortion over lossy channels of MPEG-encoded video with both inter-frame coding and intra-frame coding. A factor â is defined as the percentage of frames that are an intraframe, or I frame, i.e. a frame that is independently coded. The authors then derive the value â that inimizes distortion at the receiver. The authors of investigate optimal strategies to transmit video with minimal distortion. However, the authors assume that the I frames are received correctly and that the only loss is caused by the inter-coded frames. In this paper, we assume that any packet can be lost and rely on properties of CS video and on an adaptive parity mechanism to combat channel impairments and increase the received video quality.

System Architecture: In this section[14], we describe the overall architecture of the compressive distortion-minimizing rate controller (C-DMRC). The system takes a sequence of images at a user-defined number of frames per second and wirelessly transmits video encoded using compressed sensing. The end-to-end round trip time (RT T) is measured to perform congestion control for the

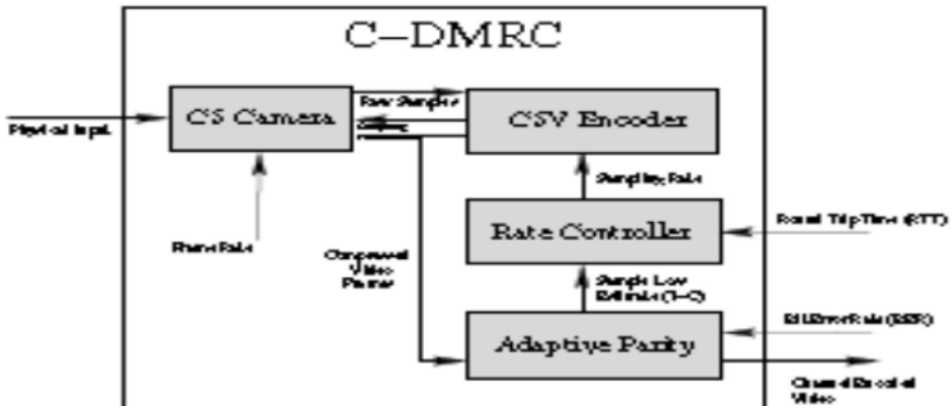

Fig. 2: Arohiectme of C-DMRC Video rate control System

video within the network and the bit error rate (BER) is measured/estimated to provide protection against channel losses. The system combines functionalities of the application layer, the transport layer and the physical layer to deliver video through a multi-hop wireless network to maximize the received video quality while accounting for network congestion and lossy channels. As illustrated in Fig. 2, there are four main components to the system, described in the following.

CS Camera: This is the subsystem where the compressed sensing image capture takes place. The details of the CS-based video representation are discussed in detail in Section IV-A1[15]. The camera can be either a traditional CCD or CMOS imaging system, or it can be a single-pixel camera as proposed in [16]. In the latter case, the samples of the image are directly obtained by taking a linear combination of a random set of the pixels and summing the intensity through the use of a photodiode. The samples generated are then passed to the video encoder.

CSV Video Encoder: The CSV video encoder is discussed in Section IV-B. The encoder receives the raw samples from the camera and generates compressed video frames. The compression is obtained through properties of CS and by leveraging the temporal correlation between consecutive video frames. The number of samples, along with the sampling matrix (i.e. which pixels are combined to create each sample, as discussed in more detail in Section IV-A) are determined at this block. The number of samples, or sampling rate, is based on input from the rate controller, while the sampling matrix is pre-selected and shared between sender and receiver.

Rate Controller: The rate control block takes as input the end-to-end RT T of previous packets and the estimated sample loss rate to determine the optimal sampling rate for the video encoder. This sampling rate is then fed back to the video encoder [17-19]. The rate control law, which is designed to maximize the received video quality while preserving fairness among competing videos, is described in detail in Section V. The CS sampling rate determined by the C-DMRC block is chosen to provide the optimal received video quality across the entire network, which is done by using the RT T to estimate the congestion in the network along with the input from the adaptive parity block to compensate for lossy channels.

Adaptive Parity: The Adaptive Parity block uses the measured or estimated sample error rate of the channel to determine a parity scheme for encoding the samples[16], which are input directly from the video encoder.

Rate Control Subsystem: In this section, we introduce the congestion-avoiding rate control mechanism for use with the compressed sensed video encoder (CSV) described in Section IV-B. The rate control subsystem both provides fairness in terms of video quality and maximizes the overall video quality of multiple videos transported through the network. To avoid network congestion, a sending node needs to take two main factors into account. First, the sender needs to regulate its rate in such a way as to allow any competing transmission at least as much bandwidth as it needs to attain a comparable video quality as itself. Note that this is different from current Internet practice, in which the emphasis is on achieving fairness in terms of data rate (not video quality). Second, the sender needs to regulate its rate to make sure that packet losses due to buffer overflows are reduced, which can be done by reducing the overall data rate if it increases to a level that the network can not sustain. To determine congestion, the round trip time RT T is measured for the transmitted video packets, where RT T is defined as the amount of time it takes for a packet to go from the source to the destination and a small reply packet to go from the destination back to the source. The change in RT T is measured as

$$\Delta \tilde{RTT}_t = \frac{\sum_{i=0}^{N-1} a_i.RTT_{b-i}}{N.\sum_{i=0}^{N-1} a_i} - \frac{\sum_{i=0}^{N-1} a_i.RTT_{b-i}}{N.\sum_{i=1}^{N} a_i}$$

which represents the difference of the weighted average over the previous N received RT T measurements with and without the most recent measurement. The weights ai are used to lowpass filter the round trip time measurements, to give more importance to the most recent RT T measurements and to make sure that the protocol reacts quickly to current network events, while averaging assures that nodes do not react too quickly to a single high or low measurement.

Conclusions and Future Work: This paper introduced a new wireless video transmission system based on compressed sensing. The system consists of a video encoder, distributed rate controller and an adaptive parity channel encoding scheme that take advantage of the properties of compressed sensed video to provide high-quality video to the receiver using a low-complexity video sensor node. The rate controller was then shown to be an implementation of an iterative gradient descent solution to the optimal rate allocation optimization problem. Simulation results show that the C-DMRC system results in a 5%-10% higher received video quality in both a network with a higher load and a small load. Simulation results also show that fairness is not sacrificed and is in fact increased, with the proposed system. Finally, the video encoder, adaptive parity and rate controller were implemented on a USRP2 software defined ratio. It was shown that the rate controller correctly reacts to congestion in the network based on measured round trip times and that the system works over real channels. We intend to implement the remaining portions of the C-DMRC system on the USRP2 radios, including image capture and video decoding. We will also measure the performance and complexity of this system compared to state-of-the-art video encoders (H.264, JPEG-XR, MJPEG, MPEG), transport (TCP, TFRC) and channel coding (RCPC, Turbo codes).

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