EFFICIENT WIRELESS IMAGE TRANSMISSION UNDER A TOTAL POWER CONSTRAINT*

S. Appadwedula, M. Goel, D.L. Jones,
K. Ramchandran, and N.R. Shanbhag
Coordinated Science Laboratory
University of Illinois at Urbana-Champaign
1308 W. Main St., Urbana, IL 61801

Abstract - Due to high data rates and limited bandwidth as well as limited battery power, wireless multimedia communications systems must be optimized in every possible way. We develop a generic matching scheme for wireless image and video communication in which the three most significant components: the source coder, the channel coder, and hardware power consumption, are jointly optimized. That is, we maximize the end-to-end image quality subject to a total power constraint on both the RF transmission power and the power consumption of the digital implementation of the channel coder, which represents a major portion of the total hardware power in short-range applications.

INTRODUCTION

Due to the rapid growth of mobile wireless communications systems, there has been an increasing demand for wireless multimedia. Wireless image and video transmission, an essential component of wireless multimedia, poses a particularly important challenge because it requires far more bandwidth than other information sources such as speech or audio. In addition, due to complex coding algorithms, the processing power can become a significant component of the battery drain.

The design of low-power wireless systems requires exploiting the tradeoff between data, redundancy and processing power based on the channel characteristics. Past work [1], [2] has shown that the tradeoff between data and redundancy can be exploited by jointly matching the source coder and channel coder to the channel characteristics. The application of joint source-channel matching in heterogeneous, multi-media environments demands general matching schemes. In [3], we developed a generic matching technique which can be applied to a wide variety of source coding standards, channel coders, and variable channel conditions. These methods maximize the

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end-to-end quality of a transmitted image subject to a constraint on the RF transmission power. However, for many applications such as portable units, the total power drain from the battery by both the RF transmitter and the digital hardware implementing the coding algorithm is more relevant. In this paper, we introduce processing power consumption as the third major component of wireless communication system design.

In past work, Lan and Tewfik [4] considered the problem of minimizing the total consumed energy of a wireless system subject to a quality-of-service constraint. They found that for low transmission power, a less efficient source coder which consumes less power but achieves less compression, combined with a channel coder adding very little redundancy, is optimal. At higher transmission power, a more efficient source coder works better by providing more information at the same data rate. These results satisfy the basic intuition about the tradeoff between source coding, channel coding, and processing power. In this paper, we introduce a more general approach to total optimization of wireless communication systems over the three domains of source coding, channel coding and processing power.

A GENERAL APPROACH TO SOURCE-CHANNEL OPTIMIZATION

The key to the joint source-channel matching scheme introduced in [3] is the end-to-end optimization over both source and channel characteristics based on a parametric distortion-vs-bit-error-rate (BER) model for source coders. This lets us construct a more general source-channel matching optimization that can be applied to a variety of source and channel coders.

Although we have developed the source model for a wide variety of coders, we will focus on progressive coders here for the benefits of scalability and graceful degradation. For the Said and Pearlman [5] (SPIHT) coder, we have found that a suitable source model of distortion (in terms of mean squared error (MSE)) on the b^{th} bit is $D(b) = \sum_{k=1}^{4} c_k e^{-l_k b}$, where c_k and l_k are parameters specific to a particular class of images.

The channel is modeled by BER as a function of symbol energy and code rate. By using BER as the common parameter between the source and the channel, the source and channel characteristics can be combined to obtain the end-to-end distortion E(D). Treating blocks of source bits equally, we have $E(D) = f(D_b(i), P_b(i), R_s)$ where $D_b(i)$ is the distortion due to losing block i, $P_b(i)$ is the probability of losing block i, and R_s is the source rate. The associated optimization problem is then

$$\min_{P_b, R_s} E(D) \text{ subject to power and/or rate constraints} \tag{1}$$

OPTIMIZATION UNDER A TOTAL POWER CONSTRAINT

In this section, we build on the source-channel optimization by introducing a channel coder with a specific hardware implementation. We express the hardware power consumption of the channel coder in terms of the coding rate and minimize the end-to-end distortion subject to a constraint on the total power consumption.

Channel Coder

With a particular choice of channel coder, an expression can be obtained for $P_b(i)$ in terms of the rate and energy in block i. The source-channel matching can then be performed over the parameters of the coders.

In [3], we found that channel coders which have both adjustable rate and adjustable energy symbols have good performance over a wide range of channel conditions. In high noise situations, adjusting the symbol energy is essential to provide adequately low BER in the channel symbols. In low noise situations, adjustable rate coders are required to provide error correction for infrequent errors. In this example, we consider a BPSK modulator which can adjust its energy per bit by allocating the transmitted energy per image E_{trans} equally to a chosen total rate $R_{tot} = ML$ bits. This total rate is allocated between source symbols and protection symbols using a Reed-Solomon (RS) coder.

With the adjustable rate and adjustable energy symbols, all the blocks are treated equally and the end-to-end distortion can be expressed as [3]

$$E(D) = \sum_{i=0}^{M-1} P_b(1-P_b)^i D_b(i) \tag{2}$$

where $P_b = f(E_{rec}, P_n, R_{tot}, t)$, E_{rec} is the received signal energy, P_n is the noise power, and $2t$ is the number of RS protection symbols in each block.

Energy Consumption Models for RS Codec

In this section, we find the energy consumption models for the Galois Field (GF) arithmetic modules, RS encoder, and decoder.

GF Arithmetic Modules Each element in GF(2^m) is defined by a m-bit binary vector. The main GF operations are addition, multiplication and inversion. For details on these operations, see [6].

The addition over $GF(2^m)$ is defined as the bit-wise sum of the m bits of two operands, requiring m XOR gates. It is assumed that standard-cell-based $0.18\mu m$, $2.5V$ CMOS technology is employed. The adder circuit was simulated via the gate-level simulator MED [7]. We found that the energy consumption per m-bit addition is given by

$$\mathcal{E}_{add} = 3.3 \times 10^{-5} m \quad (mW/MHz). \tag{3}$$

For multiplication, a bit-parallel architecture given in [8] is assumed. This architecture requires approximately $2m^2$ XOR gates and $2m^2$ AND gates for each multiplier. It was found via the MED simulation tool [7] that the energy consumption of the $m \times m$-bit multiplier is given by

$$\mathcal{E}_{mult} = 3.7 \times 10^{-5} m^3 \quad (mW/MHz). \tag{4}$$

The energy consumption per m-bit inversion is given by

$$\mathcal{E}_{inv} = 3.7 \times 10^{-5} (2m-3) m^3 \quad (mW/MHz). \tag{5}$$

In the following subsections, we employ (3)-(5) to derive the expression for the energy consumption of an RS codec.

RS Encoder Let $2t$ be the number of check symbols in the n-symbol codeword. Then, in the first $n-2t$ clock cycles, the information symbols are fed to the encoder and are simultaneously sent to the output. After $n-2t$ symbols, $2t$ latches contain the check symbols, which are then serially shifted to the output codeword. It can be shown that in each of the first $n-2t$ clock cycles, $2t$ multiply-adds are carried out. Therefore, the energy consumed per codeword generation is given by:

$$\mathcal{E}_{enc/codeword} = 2t(n-2t)\left(\mathcal{E}_{mult} + \mathcal{E}_{add}\right), \tag{6}$$

where $\mathcal{E}_{add}$ and $\mathcal{E}_{mult}$ are given by (3) and (4), respectively.

RS Decoder The majority of the RS codec power consumption is due to the RS decoder. A description of the RS decoder is beyond the scope of this paper, and the reader is referred to [6] for details. It was found that the energy consumption of the RS decoder per codeword is

$$\mathcal{E}_{dec/codeword} = (4tn + 10t^2)\mathcal{E}_{mult} + (4tn + 6t^2)\mathcal{E}_{add} + 3t\mathcal{E}_{inv}. \tag{7}$$

RS Codec Assuming that both the encoder and decoder are used for transmission and reception, the energy consumption of the codec per codeword is the sum of the energy consumption of the encoder (6) and the decoder (7)

$$\mathcal{E}_{codec/codeword} = (6tn + 6t^2)\mathcal{E}_{mult} + (6tn + 2t^2)\mathcal{E}_{add} + 3t\mathcal{E}_{inv}. \tag{8}$$

Optimization

The optimization problem of matching the source and channel coders to meet a total power constraint is

$$\min_{P_b, R_s} E(D) \text{ s.t. } P_{tot} = P_{trans} + P_{proc} + P_{other} \leq P_0 \text{ and } R_{tot} \leq R_0 \tag{9}$$

where P_{trans} is the transmitted power, P_{proc} is the power consumed by the RS encoder and decoder, P_{other} is power consumed by other components, and P_0 and R_0 are fixed power and rate constraints respectively. We can convert the power constraint to an energy constraint by dividing the power variables by the number of images/second, im, to get the energy/image. Optimization methods such as Lagrange multiplier and penalty function methods can be used to solve the constrained non-linear optimization problem.

A more natural desire from the user of a wireless communication system is for the quality of service to remain fixed while the total power is minimized to save battery life. This dual optimization problem is described as

$$\min_{P_b, R_s} P_{tot} \text{ s.t } E(D) \leq \delta \text{ and } R_{tot} \leq R_0 \tag{10}$$

Due to the duality of the distortion optimization and power optimization problems, an optimal solution of the primal problem is also an optimal solution to the dual problem.

RESULTS

In the source-channel optimization considered, the RS coder power becomes meaningful when the RS coder power is a significant component of the total transmitted power. In our optimizations, we use typical specifications of mobile wireless systems for some of the source and channel parameters and vary the other parameters to show the effect of optimization under a total power constraint.

For the source parameters, $D(b)$ was obtained for a 512×512, 8 bits/pixel gray-scale Lena image by compressing it to 1 bit/pixel and introducing bit errors. For the channel parameters, we use a maximum rate $R_0 = 512^2$ bits/image at im $= 10$ images/second and blocks of $L = 2048$ bits with $m = 8$ bit RS symbols. For simplicity, we consider a free space path loss model for the channel where pathloss $= (\frac{\lambda}{4\pi d})^2$, λ is the wavelength of the carrier frequency and d is the distance between the transmitter and the receiver. The noise power at the receiver $P_n = 1.38 \times 10^{-23} \frac{\text{J}}{^o\text{K}} T_e B_w$ where B_w is the signal bandwidth at the receiver, and $T_e = 290(\text{NF} - 1) + T_{ant}$ is the effective temperature of the receiver in ^{o}K based on the receiver noise figure (NF) and T_{ant}, the antenna temperature [9]. We use NF $= 2$ dB, a typical value for modern receivers, carrier frequency of 400 MHz, $B_w = 2.62$ MHz and $T_{ant} = 3\,^o\text{K}$ to obtain $P_n = 4.764 \times 10^{-16}$ and pathloss $= \frac{0.0036}{d^2}$.

Below is a table of optimization results for various values of P_{tot} and d all with PSNR $= 10 \log_{10} \frac{255^2}{\text{MSE}} = 36$ dB. For comparison, the results for a system achieving optimized only for transmission power are shown. For short range systems, the hardware power represents a major portion of the total power consumption, and the total-power-optimized system consumes much less power for the same performance.

System Parameters	Optimized System	Unoptimized System
$d = 10\, meters$	$M = 57, E_{proc} = 19.9\%\, E_{tot}$ $t = 12, P_{tot} = 1.082$ mW	$M = 72$ $t = 39, P_{tot} = 1.653$ mW
$d = 20\, meters$	$M = 61, E_{proc} = 12.9\%\, E_{tot}$ $t = 22, P_{tot} = 3.39$ mW	$M = 73$ $t = 40, P_{tot} = 3.74$ mW
$d = 40\, meters$	$M = 66, E_{proc} = 5.84\%\, E_{tot}$ $t = 31, P_{tot} = 11.8$ mW	$M = 73$ $t = 40, P_{tot} = 11.93$ mW

Table 1: Optimization Results for SPIHT-Adjustable Rate and Energy Coder under a Total Power Constraint (M is the number of transmitted blocks, $2t$ is the number of RS protection symbols/block)

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