JOINT SOURCE-CHANNEL MATCHING FOR JAMMING AND FADING USING AN OFDM VARIABLE QOS SOURCE-CHANNEL DESIGN

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ABSTRACT[#]

Software Defined Radios (SDR), with an architecture that provides modem flexibility and the computational resources available for application layer processing, provide a powerful and adaptive means of supporting improved transmission reliability of imagery and video. We propose an optimal, low-complexity method of transmitting digitally compressed imagery through interference-dominated and frequency-selective fading channels. The proposed method combines a wavelet-based image coder that employs phase scrambling and variable quality-of-service (VQoS) trellis-coded quantization (TCQ), and VQoS multicarrier (MC) power allocation across the channel. Optimal image quality is achieved through a joint iterative process between the image coder and MC allocation algorithm. Using our VQoS allocation method, we show that the image quality can be improved significantly, as compared to an approach that uses an arbitrary fixed joint QoS-modulation allocation across the channel. Further, this improvement extends to a variety of channels, including those that exhibit jamming interference and frequency-selective fading. The method is shown to be computationally efficient, and can thus be hosted on a handheld SDR, where computational resources are limited.

1. INTRODUCTION

Recently, there has been significant interest in robust wireless transmission of digitally compressed imagery and video due to the limited availability of RF bandwidth for broadband signals. In typical robust video and image coding schemes, the quantization is channel optimized or jointly matched to channel coding for a fixed channel bit error rate (BER) or QoS within the transmission bandwidth [1][2]. Traditional modulation approaches use fixed modulation schemes, and attempt to equalize the channel due to fading [3], while more advanced systems utilize joint source-channel coding [4] to minimize channel effects. Advanced methods can become computationally intractable for high-data-rate transmission.

Military communication systems are continually evolving, with the increased need for higher data rate waveforms. Future systems will support mobile tactical operation centers and sensor collection of critical battlefield information that will require transmission of wideband video and imagery services. Mobile operations will dynamically be establishing and re-establishing ad hoc network connections to maintain message integrity. Spectrally efficient waveforms, that minimize emitted energy for transmission, are critical to preserve precious mission resources. In addition, a communication system that dynamically adapts to changing channel conditions may further reduce energy usage, but will also improve reliability of the transmitted information.

We propose a channel adaptive technique, combined with an intelligent quality-of-service (QoS) manager, to maximize reception quality while minimizing the required transmitted signal energy. The technique uses multicarrier (MC) modulation and assigns high priority data to the best frequency domain segments of the transmit spectrum. We utilize a joint source-channel matching method that optimally matches the application layer information to the physical layer transmission capabilities. This is performed by searching for the most desirable "match" between the physical layer channel performance and the allocation of the voice, data, and/or video information to the MC sub-channels. We provide a generalized framework for autonomous optimal resource allocation regardless of the channel and the number and type of application sources, although in this work we demonstrate the performance improvements using a single source encoder.

MC modulation can be used to minimize intersymbol interference effects (simplifying equalization requirements) in wireless channels with large multipath delay spreads, by using a guard interval longer than the channel's time delay spread. MC modulation has been pro-

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posed for image transmission over spectrally-shaped channels by combining adaptive modulation, power allocation, and source coding [5]. Traditional MC methods that perform power allocation with adaptive modulation assume a constant QoS across the channel. Recently, however, an allocation process has been proposed for layered coders, where each layer exhibits a different tolerance to bit errors [6]. This approach does not change each layer's rate allocation according to channel quality, and is thus non-optimal for channels that vary significantly over time. Consequently, the layered source coder is not truly matched to the channel capacity as the channel varies. In time-varying channels that are dominated by frequency-selective fading and interference, the channel quality may often be insufficient to support a fixed strategy or a fixed QoS, thus resulting in a received image of suboptimal quality. We propose a method that optimizes the received image quality as the channel varies. This optimization is performed through a joint VQoS MC image coding allocation process.

The motivation for the proposed system is to show that for any given channel, there exists an optimal match between the QoS and number of QoS regions, MC adaptive modulation power allocation, and the number of MC channels assigned to each QoS region. For a given QoS (or BER), we define a QoS region as a group of source bits that are guaranteed to be delivered to the receiver at the specified QoS. We seek to find $\overline{Q}^*$ and $\overline{N}^*$ for any given channel, such that the maximum quality is achieved at the receiver, where $\overline{Q}^*$ and $\overline{N}^*$ are the optimum QoS choice(s), and number of MC subchannels per QoS region, respectively. To minimize system complexity, our system uses a robust VQoS image coder which does not require the use of forward error correction (FEC) coding. The MC power allocation algorithm uses actual modulation performance data to allocate bits to each subchannel. Since this procedure allows the potential use of any set of quadrature amplitude modulations, and is not based on the SNR gap approximation, it does not require a joint match between SNR gap approximation and a family of LQAM constellations [7], where L = 2, 4, 8, … 4096. The algorithm is made computationally efficient by using practical and simple lookup tables, and a fast Lagrange bisection search over each QoS region. The proposed method is very flexible and is well suited to hand-held applications where processing resources are limited.

This paper is organized as follows. Section 2 provides a description of the VQoS MC image coding system. Detailed discussions of the robust VQoS image coder and the VQoS MC power allocation algorithm are included. Coding results are presented in Section 3, and a conclusion is given in Section 4.

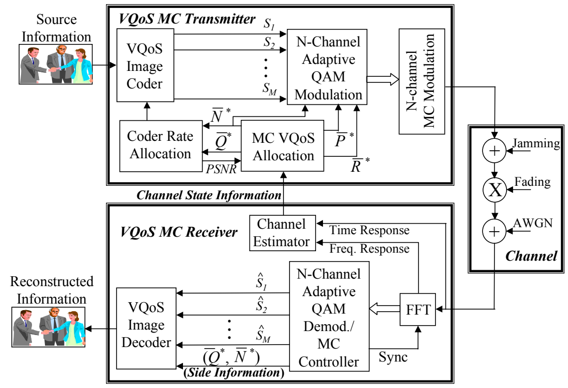

Figure 1: Joint VQoS MC image coding system.

2. SYSTEM DESCRIPTION

Figure 1 illustrates the joint VQoS MC image coding system employed for transmission in a wireless communication system. We note that the proposed method can also be applied to high-speed digital subscriber line (HDSL) MC systems. The diagram shows the application of MC adaptive modulation with power allocation to an image coder with "*M*" different bit sequences, $S_1, S_2, \ldots, S_M$. In our approach, we determine the optimal rate allocation for each QoS region bit sequence, and the optimal "match" to the MC adaptive modulation, subject to a maximum power budget. A very attractive feature of our system is that exceptional image quality is achieved without channel coding, resulting in a dramatic reduction in signal processing complexity. We show that when using our VQoS allocation method, there exists an optimum choice for the number of QoS regions, and for the MC subchannels assigned to each region. In addition, for our TCQ coder, higher image quality is achieved by iteratively solving for the best QoS strategy between the MC VQoS power allocation, and for the image coder VQoS rate allocation. A detailed description of the joint VQoS MC image coding system is given below.

2.1 VQoS multicarrier power allocation

In the literature, many algorithms have been proposed for allocating power to subchannels of a MC system. These methods are either computationally efficient, but suboptimal, or are optimal, but exhibit slow convergence. Recently, an optimal and efficient subchannel loading algorithm has been proposed that exhibits fast convergence [7]. Dual QoS loading algorithms have also been proposed recently for multicarrier systems [8]. The algorithm in [8] requires the SNR gap approximation, which can lead to QoS error in practice, and is limited to dual QoS applications. Additionally, there is a lack of research literature addressing VQoS joint source-modulation coding.

We expand the loading algorithm in [7] to *M*-region VQoS loading, and match it to *M*-region VQoS image coding. In effect, we are providing a solution for VQoS data throughput optimization, with the goal of maximizing quality by matching the channel loading to a VQoS image coder. For fixed QoS (FQoS) practical data transmission using integer-bit constellations, the data throughput optimization problem can be written [7] as

$$\max \sum_{i=1}^{N} R_i \text{ subject to: } \sum_{i=1}^{N} P_i \le P_{budget}\,,\ \mathrm{P}_{e,i} \le \mathrm{P}_{error}\ \forall i, \quad (1)$$

where R_i, P_i, and $\mathrm{P}_{e,i}$ are the i^{th} channel rate (in bits/symbol), power allocation, and error probability, respectively, P_{error} is a fixed bit error rate constraint, and P_{budget} is the total power constraint. For the VQoS case, the data throughput optimization problem can be reformulated and expressed as

$$\max \sum_{i=1}^{N_q} R_i^q \text{ subject to: } \sum_{i=1}^{N_q} P_i^q \le P_{budget}^q\,,\ \mathrm{P}_{e,i}^q \le \mathrm{P}_{error}^q\ \forall i, \quad (2)$$

where q represents the particular QoS region, and q = 1, 2, …, M. In addition, it is necessary to define the power budget for each QoS region under the constraint

$$\sum_{q=1}^{M} P_{budget}^q \le P_{budget}\,, \quad (3)$$

where P_{budget} is defined as in (1).

The optimization problem in (2) and (3) can then be reformulated as an unconstrained optimization problem[1] by merging the rate and power using a Lagrange multiplier in each QoS region. This process can be written as

$$\min J^q(\lambda) = -\sum_{i=1}^{N_q} R_i^q + \lambda_q \sum_{i=1}^{N_q} P_i^q\,, \quad (4)$$

where $J^q(\lambda)$ is the Lagrange cost, and $\lambda \ge 0$. For a fixed λ, the cost is minimized when $\partial J^q(\lambda)/\partial P_i^q = 0$, for all i in each QoS region. Here, R_i^q is a function of P_i^q that satisfies $\mathrm{P}_{e,i}^q \le \mathrm{P}_{error}^q\ \forall\ i$ in each QoS region[2]. Lagrange cost is minimized when rates and powers over all subchannels in each region can be derived from the rate-versus-power curve operating point with slope, λ. Total power for λ is computed by summing the allocated power to each subchannel in the region. Our goal is to find the optimal λ^*, or $\lambda_1^*, \lambda_2^*, \lambda_3^*, ..., \lambda_M^*$ combination, over all QoS regions. If we know the channel-to-noise ratio (CNR), we can write the following VQoS cost minimization, which is used for developing efficient loading [7]:

$$\frac{\partial R_i^q(SNR_i^q)}{\partial (SNR_i^q)} CNR_i^q = \lambda_q \text{ for } i = 1, 2, 3, \ldots, N_q, \quad (5)$$

where $SNR_i^q = (P_i^q T\,|\,H_i^q\,|^2 / 2\sigma_i^2)$, $CNR_i^q = (T\,|\,H_i^q\,|^2 / 2\sigma_i^2)$, T is the symbol period, $|\,H_i^q\,|^2$ is the subchannel gain, and σ_i^2 is the subchannel noise power. For VQoS optimization, we order the channel quality from best to worst and assign the best channel(s) to the lowest QoS (BER) requirement [8]. For example, a QoS region with $\mathrm{P}_{error}^q = 10^{-4}$ would be assigned to better quality channels than a QoS region with $\mathrm{P}_{error}^q = 10^{-2}$.

Once a bit allocation is determined for each QoS region, this information is provided to the VQoS image coder, and an optimal rate allocation is performed according to the allotted bit rates for each QoS. Quality and rate estimates are then passed back to the MC allocation algorithm. Bit rate, source-quality, and source-rate parameters can be passed between the MC and image coder allocation algorithms, and the best quality solution is found using multiple iterations. This joint iterative procedure yields the optimal quality for the given channel condition.

2.2 Robust VQoS image coder

The image coding algorithm utilized in the present work is based upon the coder presented in [2]. The input image is first decomposed into 22 subbands using a modified Mallat tree decomposition. The statistics of each subband are computed, and all subbands are normalized to zero-mean and unit-variance. Each normalized subband is then all-pass filtered by a phase scrambling stage. The filtered subbands are encoded using a fixed-rate TCQ system designed for the memoryless Gaussian source.

For the VQoS system presented here, an iterative rate allocation scheme has been developed, which provides an optimal allocation of bits, given the VQoS parameters. That is, for each subband, i (i = 1,2,…,K), the rate allocation scheme uses the computed subband statistics and the VQoS parameters, and selects a r_i-bit TCQ codebook, $0 \le r_i \le 10$, from the designed TCQ codebooks, so that the overall distortion is minimized, while maintaining the specified overall bit rate, R_T.

[1]From [7], this reformulation is shown to be equivalent provided the rate is a convex function of power, which is true for all signal constellations we use in this work.

[2]For M=1, it is shown that meeting the error-probability with equality is optimal [7].

Let $\overline{Q}$ = [Pb_1,Pb_2,…,Pb_M], and $\overline{B}$ = [B_1,B_2,…,B_M], be the set of allowable bit error probabilities, and the set of allowable bits per QoS spectral region, respectively. Given $\overline{Q}$ and $\overline{B}$, we wish to determine the optimal rate allocation vector, $\overline{b}^*$ = [r_1,r_2,…,r_K], and subband QoS assignment vector, $\overline{sb\_QoS}$ = [Pb_1,Pb_2,…,Pb_K], such that $E_s = \sum_{i=1}^{K} \alpha_i \sigma_i^2 E_{ij}(r_i)$ is minimized, subject to an average rate constraint of $\sum_{i=1}^{K} \alpha_i r_i \le R_T$ bits/coefficient, where σ_i is the standard deviation of sequence i, $E_{ij}(r_i)$, $1 \le i \le K$, $1 \le j \le M$, denotes the rate-distortion performance of the j^{th} TCQ quantizer (i.e., TCQ designed for Pb_j) at r_i bits/sample, K is the number of subbands, and α_i is a weighting coefficient that accounts for the variability in sequence length. Note that for a 22-subband decomposition, K = 22. The rate allocation proceeds as follows:

1. Initialization: Let $B_{tot} = \sum_{m=1}^{M} B_m$ be the total number of bits per image, L_i be the number of coefficients in subband i, j = 1 for all subbands (i.e., $\overline{sb\_QoS}$. = Pb_1), and $R_T = B_{tot}/WV$, where W and V are the number of image rows and columns, respectively. Find $\overline{b}^*$ as outlined in [2]. Let $\overline{b}^*_{prev}$ = $\overline{b}^*$, and $\overline{sb\_QoS}^*_{prev}$ = $\overline{sb\_QoS}$.
2. Subband QoS assignment: Compute the number of bits assigned to subband i, $L_i r_i$. For each Pb_j, $1 \le j \le M$, determine which subbands, ordered from highest to lowest rate allocations, fit entirely within each Pb_j bit budget, B_j. Assign these subbands to Pb_j, to form $\overline{sb\_QoS}^*$. Note: Remaining bits from Pb_j are assigned to Pb_{j+1}.
3. Rate allocation: Calculate $\overline{b}^*$ as in Step 1, using the new QoS assignments, $\overline{sb\_QoS}^*$, from Step 2.
4. If $(|(\overline{b}^*_{prev} - \overline{b}^*)| + |(\overline{sb\_QoS}^*_{prev} - \overline{sb\_QoS}^*)|) < \varepsilon$, quit; otherwise, $\overline{b}^*_{prev} = \overline{b}^*$, $\overline{sb\_QoS}^*_{prev} = \overline{sb\_QoS}^*$, go to Step 2.

2.3 VQoS MC allocation algorithm

Computing the composite rate-power curve for all operating points is intractable, so a less expensive iterative solution is used to find λ_q^*. This is performed by first estimating λ_q, its corresponding total power, and updating such that convergence to an optimal solution is achieved. Lookup tables, containing operating point slope bounds, are used to avoid direct computation of the operating point for each subchannel. Rate-SNR tables are generated for the desired modulation types, which are invariant to channel conditions, and are used to assign the respective rate and power corresponding to λ_q. The Lagrange minimization in (5) gives the optimal operating point, $\beta_i^q = (\lambda_q / CNR_i^q)$, of the rate-SNR function of each subchannel for each QoS region. Once beta is determined for each subchannel and QoS region, the lookup tables are used to find the rate-SNR operating point, and the power and rate allocations can be computed using:

$$P_i^q = SNR(\beta_i^q)/CNR_i^q \qquad R_i^q = R(\beta_i^q) \qquad P_{totq}^q = \sum_{i=1}^{N_q} P_i^q$$

$$R_{totq}^q = \sum_{i=1}^{N_q} R_i^q \qquad P_{total} = \sum_{q=1}^{M} P_{totq}^q \qquad R_{total} = \sum_{q=1}^{M} R_{totq}^q . \quad (6)$$

The bit allocations are determined such that the maximum rate is achieved, given the QoS constraints for each region, subject to the power budget constraint as defined in (3). The algorithm can be summarized as follows:

1. Load lookup tables and sort channel according to quality.
2. Input M QoS regions, and the constraints for each region.
3. Assign P_{budget}^q to each QoS region.
4. Begin Loop for each QoS region.
5. Perform efficient power allocation as defined in [7].
6. Send bit allocations for each QoS region to image coder.
7. Perform VQoS rate allocation in image coder.
8. Return estimated quality, determine if quality is maximum.
9. If quality is maximized, transmit information; Otherwise, change either M, or the constraints for each QoS, or both; go to Step 2.

2.4 Frequency selective and interference channels

We chose to evaluate the robust transmission method for three different channels, as shown in Figure 2. The MC system uses adaptive QAM constellations, with 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 bit/symbol signaling choices. All constellations were Gray coded such that, for sufficient SNR, only a single bit error is experienced for symbol errors to neighboring constellation points. Figure 3 shows the resulting bit/symbol allocation for channel 1 with QoS strategy = [10^{-1} 10^{-2} 10^{-3} 10^{-4}], and 64 subchannels assigned to each QoS region. We note that this strategy would be represented in Table 1 as $\overline{N}_{\overline{Q}}$ = [64_1 64_2 64_3 64_4]. For cases where $Pb_n \ne 10^{-m}$, where n = 1, 2, …., M and m = 1, 2, 3, 4, or 5, Pb_n is defined exactly.

3. RESULTS

We applied the iterative image quality optimization procedure and evaluated the quality at various QoS strategies using objective (Peak SNR) and subjective (visual) measures. To assure a fixed image delivery rate, we assigned

130 MC blocks per image, and a MC block (symbol) time of approximately 256 µsec. This supports a 30 image/sec

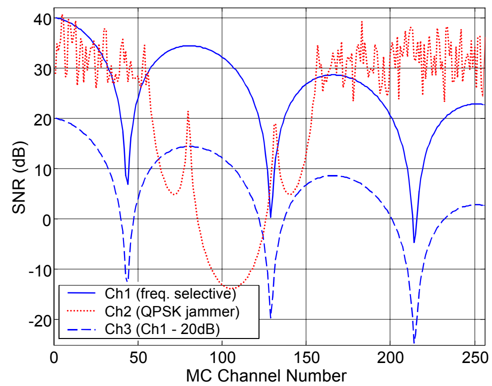

Figure 2: SNR characteristics for channels 1, 2, and 3.

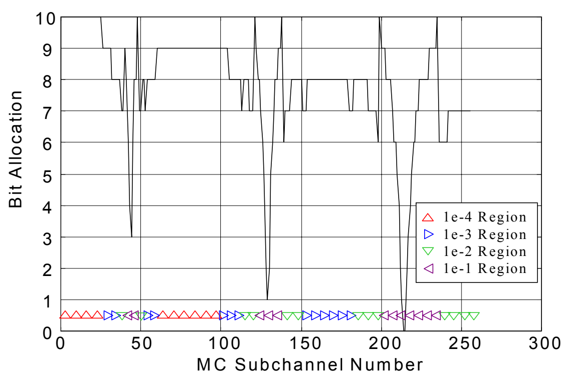

Figure 3: Example VQoS bit allocation for channel 1.

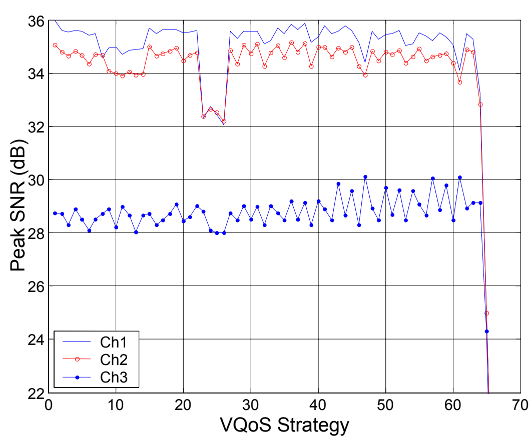

Figure 4: Peak SNR results versus strategy.

frame rate, which is sufficient for high-quality video applications. The total number of MC subchannels per block is equal to 256. In Table 1, we compare three transmission methods: VQoS^M, VQoS^1, and FQoS/QAM. VQoS^M and VQoS^1 both use adaptive modulation, with the VQoS^1 system having a single QoS region (i.e., q = 1). The FQoS/QAM system adapts the fixed modulation order (given the channel bit error rate), such that the peak SNR

*Represents maximum measured average PSNR for each method in given channel

Transmission Method	Chnl	PSNR* (dB)	$\overline{N}_{\overline{Q}}$ =[$N1_{QoS1}$ $N2_{QoS2}$ $N3_{QoS3}\ldots NM_{QoSM}$]	ΔPSNR (dB)
VQoS^M/MQAM	1	36.0	[64_2 64_3 64_4 64_5]	
VQoS^1/MQAM	1	35.5	[256_5]	-0.5
FQoS/4QAM	1	26.3	[$256_{3.4X10^{-3}}$]	-9.7
VQoS^M/MQAM	2	35.2	[192_3 64_5]	
VQoS^1/MQAM	2	34.9	[256_5]	-0.3
FQoS/8QAM	2	18.8	[$256_{4.7X10^{-2}}$]	-16.4
VQoS^M/MQAM	3	30.1	[224_2 32_5]	
VQoS^1/MQAM	3	29.1	[256_4]	-1.0
FQoS/BPSK	3	18.7	[$256_{4X10^{-2}}$]	-11.4

Table 1: Performance results for each transmission method.

Figure 5: Reconstructed Lenna image: FQoS (left), VQoS (right).

(PSNR) is maximized for each transmitted image. Figure 4 shows the average PSNR results for each channel. The reported PSNR was determined by averaging 20 different transmissions through each channel. By performing the proposed algorithm over many channels, including those shown in Figure 4, we found the VQoS^M optimization process can result in a performance improvement of at least 2 dB. The VQoS^M method was found to perform better than VQoS^1 in all channels, with increasing ΔPSNR as the channel degrades (compare ΔPSNR between channels 1 and 3). Figure 5 shows the visual quality of the 512 X 512 Lenna image for VQoS^M and FQoS/BPSK, when transmitted through channel 3. In this example, the improvement (ΔPSNR) is greater than 11 dB.

4. CONCLUSIONS*

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A method is presented that utilizes the flexibility in the modem and application layer computational resources of an SDR, which maximizes the reception quality of digitally compressed imagery. A robust, low-complexity method of transmitting digital video and imagery is proposed for transmission over channels dominated by frequency-selective fading and interference. The presented method is called variable QoS (VQoS) joint source-modulation coding. The VQoS MC power allocation routine is based upon lookup tables derived from actual modulation performance curves, and can be stored very efficiently in handheld SDR memory. The image encoder also utilizes an efficient VQoS rate allocation procedure. The proposed system produces exceptional image quality without the use of channel coding or channel-optimized quantization. The computationally efficient VQoS MC allocation procedure, combined with the VQoS robust source encoder, make the proposed system very attractive for small, portable electronic SDR transceivers. The joint source-channel matching method can be made even more efficient by accepting user defined parameters programmed into the SDR, such as source class priority, QoS and bandwidth constraints, as part of mission constrained resource requirements.

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