OPTIMAL CARRIER LOADING FOR MAXIMIZING VISUAL ENTROPY OVER OFDMA CELLULAR NETWORKS

Uk Jang, Hyungkeuk Lee and Sanghoon Lee

Wireless Network Lab., Center for IT of Yonsei University, Seoul, Korea, 120-749.
E-mail: {ukjang, punktank, slee}@yonsei.ac.kr

ABSTRACT

Explosively increasing demands for the wireless multimedia data have accelerated to research for adapting higher quality video applications in extensive efforts. In this paper, we explore a theoretical approach to cross-layer optimization between multimedia and wireless network by means of a quality criterion termed "visual entropy" for downlink video transmission, using a layered coding algorithm. We obtain the optimal loading ratio through an optimization problem, which aims at balancing the trade-off relationship between ICI (Inter-Cell Interference) and channel throughput. In the simulation, we show that the throughput gain in terms of visual entropy at the cell boundary is increased by up to about 32%.

Index Terms— Cross-layer Optimization, OFDM (Orthogonal Frequency Division Multiplexing), Loading Ratio, SVC (Scalable Video Coding), Visual Entropy

1. INTRODUCTION

Due to the increasing demand of wireless multimedia data, extensive studies have been conducted for adapting higher quality video applications centering around the standard series of JPEG, MPEG, H.264 and etc,. This technical trend leads to an increase in wireless channel capacity by the use of broader bandwidth, and a considerable effort has been made for more efficient radio resource utilization. However, there are many limitations for applying directly the magnificent growth of multimedia traffic into expensive and capacity limited wireless channels. Thus, the radio resource management for multimedia transmission has been emerging as one of the most interesting and challenging issues.

In an effort for joint cooperation between multimedia and wireless transmission, some recent papers have dealt with the issue of cross-layer optimization for achieving a better quality of source over a capacity-limited wireless channel [1][2]. In [1], authors have tried to exploit an adaptive transmission algorithm for the downlink OFDM (Orthogonal Frequency Division Multiplexing) system. In addition, authors in [2] presented an unequal power allocation scheme for transmission of JPEG compressed images over multiple-input multiple output systems employing spatial multiplexing. These literatures have focused on a heuristic algorithm to find the solution for optimization rather than on a theoretical and mathematical method.

In this paper, we explore a theoretical approach to cross-layer optimization between multimedia and wireless network by means of a quality criterion termed "visual entropy" for downlink video transmission, using an SVC (Scalable Video Coding) algorithm. By a layered coding algorithm used in the SVC, the transmitted bitstream can be decomposed into various layers based on the cutoff frequency. The network-adaptive loading control is then applied to each layer. In particular, the base layer needs to be handled more carefully, because the base layer contains more important visual information among several layers. We will obtain the optimal loading ratio of carriers through an optimization problem, which is for balancing the trade-off relationship between interference and throughput. From the perspective of "visual entropy", an optimal resource allocation is conducted to deliver more visually important data via the optimization problem.

2. MOTIVATION

OFDM has been known as the most suitable modulation mechanism for supporting such high data rates due to its high spectral efficiency. In spite of this advantage, however, the channel throughput at the cell boundary is rapidly decreased due to ICI (Inter Cell Interference) as shown in Fig. 1. Therefore, it may not entertain multiple users while maintaining uniformly a certain level of QoS (Quality of Service).

In order to prevent the quality degradation relying on the location of MSs (Mobile Stations), it is necessary to develop an interference mitigation technique. As a strategy, the carrier loading ratio, which represents the fraction of the number of used sub-carriers and the number of the total sub-carriers over a certain subband, can be employed differently according to the amount of data loaded. If the loading ratio is increased, the probability of carrier collision with other sub-carriers of neighboring cells is increased. On the other hand, if the load-

This work was supported by the Korea Science and Engineering Foundation grant funded by the Korea government (MOST) (No.R01-2007-000-11708-0), and by Seoul Research & Business Development Program (11136M0212351).

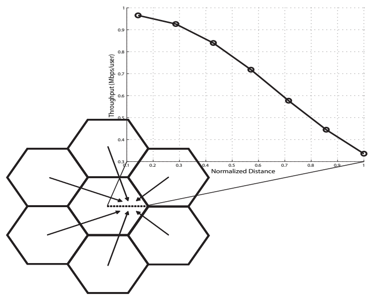

Fig. 1. Throughput over a multicell environment.

ing ratio is reduced, the collision probability can be also decreased due to the less use of sub-carriers.

By the layered coding algorithm, a transmitted frame of an original video is divided into several layers. The base layer comprises the information of low frequency, which is particulary sensitive to the HVS (Human Visual System). On the other hand, the enhancement layer contains the information of high frequency which is relatively less-sensitive to the HVS. If each layer has the different amount of visual information based on the HVS, the volume of delivered visual data can be more appropriately manipulated. In recent literatures [3][4], we have proposed "visual entropy", which represents the quantity of the visual importance in bits. Utilizing the criterion, the bitstreams of the base and enhancement layers can be dealt with in the wireless network.

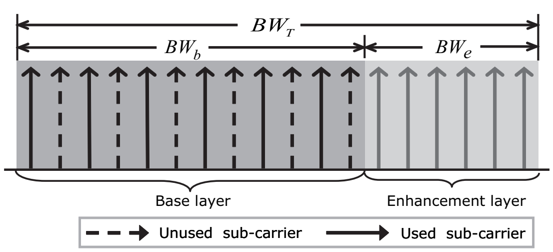

Fig. 2. A scenario of the proposed system.

Figure 2 depicts briefly the proposed system model. The base layer information is allocated to the subband (BW_b) more sparsely with a low loading ratio, and the enhancement layer information is allocated to the subband (BW_e) more densely with a high loading ratio. Therefore, it is possible to experience less severe interference over BW_b relative to BW_e due to the reduced collision probability. In such a case, the user located at the cell boundary can obtain the data of the base layer more reliably.

As the loading ratio is increased, the total throughput over the cell is also increased, which also leads to an increase of the ICI at the cell boundary as the side effect. On the contrary, as the loading ratio is decreased, the ICI can be reduced, but the spectral efficiency of each carrier is dropped. Thus, it is important to decide the loading ratio for balancing the trade-off relationship between ICI and total throughput.

3. VISUAL ENTROPY & WEIGHT MODELING

For a given quantized parameter q, the empirical entropy (in bits per pixel) $h(\sigma^2)$ was introduced in [5] by

$$h(\sigma^2) = \begin{cases} \frac{1}{2}\log_2\left(2e^2\frac{\sigma^2}{q^2}\right), & \frac{\sigma^2}{q^2} > \frac{1}{2e} \\ \frac{e}{\ln 2}\frac{\sigma^2}{q^2}, & \frac{\sigma^2}{q^2} \leq \frac{1}{2e}. \end{cases} \quad (1)$$

To adjust the prediction error due to the traffic variation, we obtained the following empirical rate in [3]:

$$r(\sigma_x^2) = \alpha_x h(\sigma_x^2) + \beta_x, \quad (2)$$

where α_x and β_x are constants. Suppose that Z_x is a random variable of σ_x^2. The random variable R_x associated with $r(\sigma_x^2)$ can then be expressed by $R_x = \alpha_x Z_x + \beta_x$. The expected value and variance of R_x are then $E[R_x] = \alpha_x E[Z_x] + \beta_x$ and $VAR[R_x] = \alpha_x^2 VAR[Z_x]$, where $\alpha_x = \sqrt{VAR[R_x]/VAR[Z_x]}$ and $\beta_x = E[R_x] - \alpha_x E[Z_x]$.

In case of the layered coding, where the base layer is extracted from the original frame w.r.t. the cutoff frequency f_c, the empirical rates for the base and the enhancement layers are, similarly, obtained by (2). Using the variances (${\sigma_b}^2$ and ${\sigma_e}^2$) and expected values of macroblocks in the base and enhancement layers, the constants α_b and β_b can be obtained. Using (2), the empirical rate of the base layer, $r(\sigma_b^2)$ and $r(\sigma_e^2)$, can be then obtained by

$$\begin{aligned} \text{Base layer} &: r_b(\sigma_b^2) = \alpha_b h(\sigma_b^2) + \beta_b, \\ \text{Enhancement layer} &: r_e(\sigma_e^2) = \alpha_e h(\sigma_e^2) + \beta_e. \end{aligned} \quad (3)$$

In [6], the visual weight of each layer is represented as follows,

$$w_{total} = \int\int_D p(f_1, f_2)\, CS(f_1, f_2)\, df_1 df_2, \quad (4)$$

$$w_b = \frac{\int_0^{\frac{\pi}{2}}\int_0^{f_c} \kappa\ \exp(-\mu r)\, r dr d\theta}{w_{total}}. \quad (5)$$

$$w_e = \frac{\int_0^{\frac{\pi}{2}}\int_{f_c}^{f_{max}} \kappa\ \exp(-\mu r)\, r dr d\theta}{w_{total}}. \quad (6)$$

where $p(f_1, f_2)$ is the joint pdf of the two-dimensional spatial frequencies, f_1 and f_2 are the spatial frequencies (cycle/degree), $CS(f_1, f_2)$ is two-dimensional contrast sensitivity function, κ and μ are constants. Since the amount of visual information for the base layer varies according to the cutoff frequency f_c, the visual weights of the base and enhancement layers become the functions of f_c.

4. LINK CAPACITY ANALYSIS FOR OFDMA SYSTEMS

Without loss of generality, let an MS be located at x in the i^{th} cell (home cell) throughout the paper. The path loss between the MS and an adjacent BS (Base Station)(here, the j^{th} BS) of the i^{th} BS is given by $L(j,x)$=$r_{(j,x)}^{-p}10^{\xi_{(j,x)}/10}$ where p is a path-loss exponent (typically three to four), $r_{(j,x)}$ is the distance between x and the j^{th} BS, and $\xi_{(j,x)}$ is a Gaussian distributed random variable with a zero mean and a standard deviation representing shadowing. The ICI is given by $I_{i,x}^{o} = \sum_{j=1}^{N_{oc}} S \cdot L(j,x)$, where N_{oc} is the number of neighbor cells (N_{oc}=18 in the 1^{st} and 2^{nd} tiers).

In this scheme, the number of users in a cell is assumed to be uniformly distributed. In addition, a carrier selection is randomly performed according to a loading ratio ρ. The carrier selection probability $\tilde{P}$ is obtained by $\tilde{P} = \hat{n}_{sc}/n_{sc} = \rho$ where n_{sc} is the number of sub-carriers allocated to each user and $\hat{n}_{sc}$ is the number of used sub-carriers among them ($\hat{n}_{sc} = \rho \cdot n_{sc}$). Since the sub-carrier selection of each cell is totally independent of each other, the collision probability between the i^{th} and j^{th} cells becomes $P_{y_{i,j}}(y_{i,j} = 1) = \tilde{P}^2$. The ICI of the home BS occurs when the same sub-carrier is selected by both the home BS and the other adjacent BSs. The ICI (I^o) at x position in the i^{th} cell is then given by

$$I_{i,x}^{o} = \sum_{j=1}^{N_{oc}} S \cdot L(j,x) \cdot \rho^2, \tag{7}$$

In general, the SINR (Signal to Interference plus Noise Ratio) for a carrier at the x position in the i^{th} cell is given by

$$SINR_{i,x} = \frac{S \cdot L(i,x)}{I_{i,x}^{o} + I_{i,x}^{s} + N_0 BW_s}, \tag{8}$$

where N_0 is the power spectral density of the AWGN (Additive White Gaussian Noise), S is the transmitted power for each carrier and BW_s is the bandwidth of a sub-carrier. Using Eqs. (7), (8) and I^o+$I^s \gg N_0 BW$, the SINR formula is obtained by

$$SINR_{i,x} = \frac{S \cdot L(i,x)}{\sum_{j=1}^{N_{oc}} S \cdot L(j,x) \cdot \rho^2}. \tag{9}$$

5. OPTIMAL CARRIER LOADING RATIO

Using (9), the SINR formula of each layer (i.e., base and enhancement layer) becomes

$$SINR_{i,x}^{l} = \frac{S \cdot L(i,x)}{\sum_{j=1}^{N_{oc}} S \cdot L(j,x) \cdot \rho_{l,x}^2}, \tag{10}$$

where l is the layer index (assume that 1 for base layer and 2 for enhancement layer in this system) and $\rho_{l,x}$ is the loading ratio for the l^{th} layer where an MS is located at x position (the loading ratio for the enhancement layer $\rho_{2,x}$ is assumed to 1). Since the channel capacity means an upper bound of deliverable data, it is assumed that the channel capacity is equal to the data rate. The channel capacity is obtained using the Shannon capacity formula as follows:

$$\begin{aligned} C_{l,x}(\theta_{l,x},\ \rho_{l,x}) &= N_{sc}\, \theta_{l,x}\, \rho_{l,x}\, BW_s\, \log(1 + SINR_{i,x}^{l}) \\ &= r_l(\sigma_l^2) = \alpha_l h(\sigma_l^2) + \beta_l. \end{aligned}$$

where N_{sc} is the total number of sub-carriers, $\theta_{l,x}$ is the bandwidth ratio for the l^{th} layer where an MS is located at x position and $r_l(\sigma_l^2)$ is the empirical rate model for the l^{th} layer in (3). In addition, the visual entropy known as the weighted entropy is expressed by

$$\begin{aligned} C_{l,x}^{w}(\theta_{l,x},\ \rho_{l,x}) &= w_l\, r_l(\sigma_l^2) \\ &= w_l\, N_{sc}\, \theta_{l,x}\, \rho_{l,x}\, BW_s\, \log(1 + SINR_{i,x}^{l}) \end{aligned}$$

where ω_l is the visual weight of l^{th} layer in (5) and (6).

For point-to-point visual communications, the loading control needs to be accomplished for maximizing the throughput of visual entropy. The optimization problem for transmitting the visual information at each normalized distance can be formulated as follows,

$$\max_{\theta_{l,x},\rho_{l,x}} \quad \sum_{l=1}^{L} C_{l,x}^{w}(\theta_{l,x},\ \rho_{l,x}) \tag{11}$$

$$\text{subject to} \quad \sum_{l=1}^{L} \theta_{l,x} \cdot \rho_{l,x} \le 1 \ \ \forall x, \tag{12}$$

$$\sum_{l=1}^{L} \theta_{l,x} = 1 \ \ \forall x, \tag{13}$$

$$0 < \rho_{l,x} \le 1 \ \ \forall x. \tag{14}$$

The constraint in (12) is the total bandwidth constraint, i.e., the allocated bandwidth to each layer does not exceed the total bandwidth. The constraint in (13) indicate that the sum of the bandwidth ratios of all layers is equal to one. The sub-carrier loading ratio of each layer exists in the range of $(0, 1]$ at the last constraint in (14). The sub-carrier loading and bandwidth ratios have different optimal values according to the distance. Since the channel condition is dependent on the position for point-to-point visual communications, the optimal values of two variables are needed to be dynamically determined. However, the problem above is computationally intractable so that we propose an algorithm for finding optimal values of $\rho_{l,x}^{*}$ and $\theta_{l,x}^{*}$ for each layer from the perspective of maximizing visual entropy at each location.

step 1. $\theta_{1,x}$ is set to 1. → we can find $\rho_{1,x}^{*}$, since (11) is the concave function.
step 2. Using $\rho_{1,x}^{*}$ obtained from $step1$, the optimal bandwidth is chosen to support the target data rate of each layer.

Since the base layer contains more visually important data, the visual weight of the base layer is much larger than that of the enhancement layers. Thus, the bandwidth of the base layer is determined prior to the enhancement layers, and the remaining bandwidth is allocated to the enhancement layers.

6. SIMULATION RESULTS & CONCLUSION

In the simulations, the following simulation parameters are used: the entire bandwidth of 8.75 MHz, the total number of sub-carriers (N_{sc}) of 1024, the cut-off frequency (f_c) of 0.15, and the total number of users of 100, and the total number of BSs of 18.

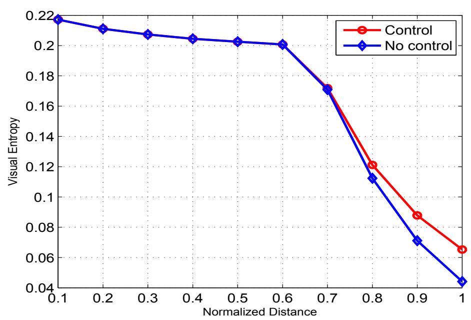

Fig. 3. Visual entropy according to the normalized distance.

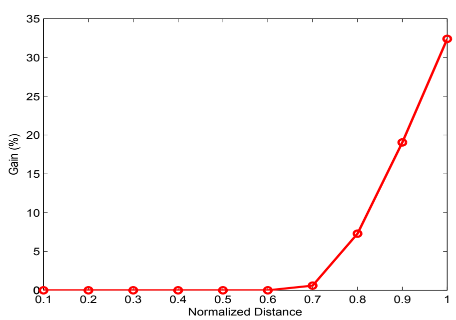

Fig. 4. Visual entropy gain according to the normalized distance. At the cell boundary, the visual entropy gain is about 32.39%.

Figure 3 shows the visual entropy with the loading ratio control and without the use of loading ratio control according to the normalized distance from the home BS over a multi-cell environment. It is easy to find that much enhanced channel capacity can be obtained by controlling the loading ratio at the cell boundary. Figure 4 represents the visual entropy gain for the proposed scheme. The throughput gain in terms of the visual entropy at the cell boundary is increased by up to about 32.39%. Figure 5 shows the visual qualities of the reconstructed frames for the two cases at the cell boundary.

Fig. 5. The reconstructed frames, (a) no loading ratio control (b) loading ratio control when an MS is located at the cell boundary (the normalized distance of 0.95).

At the cell boundary, it can be seen that the visual quality of the proposed scheme in Fig. 5 (b) is much better compared to Fig. 5 (a).

In this paper, a theoretical approach to cross-layer optimization between application and wireless link layers was studied by exploiting the merit of the SVC. Using the criterion of the visual entropy, the carrier loading ratio was determined through the cross-layer optimization approach. In addition, the optimal solution has resulted in maximizing the total visual entropy and mitigating the ICI.

7. REFERENCES

[1] L. Li, G. Zhu, X. Xiao and J. Liu, "QoS-guarantee Cross-layer Adaptive Transmission for Downlink Wireless OFDM ," *Proc. Int. Conf. Wireless Comm., Networking and Mobile Computing,* vol.1, pp. 181-184, Sep. 2005.

[2] M. F. Sabir, R. W. Heath Jr. and A. C. Bovik, "Unequal Power Allocation for JPEG Transmission over MIMO Systems," *Conf. Record of the Thirty-Ninth Asilomar Conf. on Signals, Systems and Computers,* pp. 1608-1612, 2005.

[3] H. Lee and S. Lee, "Compression Gain Measurements by Using ROI-based Data Reduction," *IEICE Trans. on Fundamentals,* vol.E89-A, no.11, pp. 2985-2989, Nov. 2006.

[4] H. Lee and S. Lee, "Visual Entropy Gain for Wavelet Image Coding," *IEEE Signal Processing Letters,* vol. 13, no. 9, pp. 553-556, Sep. 2006.

[5] J. Ribas-Corbera and D. Neuhoff, "On the Optimal Motion Vector Accuracy for Block-based Motion-compensated Video Coders," *Proc. IS&T/SPIE Dig. Video Comp.: Alg. & Tech.,* pp. 302-314, Jan.-Feb. 1996.

[6] J. Park, H. Lee and S. Lee, "Cross-Layer Optimization for Scalable Video Coding and Transmission over Broadband Wireless Networks," *IEEE Int. Conf. on Image Processing,* Sep. 2007.