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Proposal for a cross layer scheme for real-time wireless video

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Abstract: This paper focuses on the design of the cross layer between the video application layer and the MIMO physical layer. MIMO physical layer research has promised an enormous increase in the capacity of wireless communication systems. Also MIMO wireless systems operate under fading conditions where the channel faces arbitrary fluctuations. Since the wireless channel changes over each coherence period, the capacity of the wireless channel, given the power constraints, changes. Hence to make efficient use of the available capacity one needs to adapt the video bit rate. However it is impossible to adapt at the application layer as changing the parameters of the video takes more time than the coherence period of the channel. In this paper we address this problem through a novel solution and also investigate its performance through a simulation study.

Key words: MIMO, V-BLAST, Adaptive modulation, Diversity, Constant bit rate (CBR), Cross layer design, Power control, Fine granular scalability (FGS)
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INTRODUCTION

Increase in wireless system capacity through 3G services and innovative low bit rate video coding techniques have made it possible to have mobile multimedia services on hand-held systems. High quality real-time multimedia services are slowly being deployed on hand-held systems. However large scale deployment at low cost is still to be realized due to technological challenges such as stringent power control under severely fading environments and the susceptibility of high quality compressed multimedia data to errors. This paper proposes a novel design mechanism of the cross layer between the physical and application layer that provides efficient video transmission under a quality of service that takes care of the above problems.

THE NEED FOR DESIGN OF CROSS LAYER BETWEEN APPLICATION AND PHYSICAL LAYER

The physical layer design for wireless channels mainly aims at maximizing the channel capacity or battery life of hand-held systems. One could provide better quality video stream if the available physical layer capacity is properly utilized by the application. An obvious approach is for the application layer to change the source bit rate according to the available channel capacity. This calls for proper design of the cross layer between the physical layer and application layer. If the application layer has to appropriately modify the source bit rate with the available capacity, then the channel information will need to be passed to the application layer for every coherence period.

However to adapt the source encoding bit rate requires a time period longer than the channel coherence period at the application layer. So any information utilized at the application would be virtually of no use by the time the bit rate is adjusted at the application layer. However if it could be possible to modify the source bit rate intelligently at the physical layer with a gradual degradation of image quality, this could overcome the problem. In this paper we propose a novel way to seamlessly integrate the real-time video encoder and the wireless channel to adapt to the fading conditions and maintain the highest possible quality.

CROSS LAYER SOLUTION

Physical layer technique

At the physical layer, spectrum and power are the scarce resources. Since available spectrum is fixed, the transmission power must be managed efficiently. We develop a MIMO physical layer technique that utilizes adaptive modulation (Wolniansky *et al.*, 1998; Raleigh and Cioffi, 1996; 1998; Winters *et al.*, 1994) and allocates the maximum possible bits under a power constraint at a constant bit error rate (BER). In typical video communications, one needs to satisfy a minimum quality of service (QoS) requirement. We take the minimum QoS to be a guaranteed minimum number of bits, R, transmitted for all periods outside outage under a constant BER. We set the peak power required so that at least R bits will be transmitted under all non-outage periods under BER constraint.

We consider the channel model as in V-BLAST. Let the transmitter has M antennas and the receiver has N antennas with $N \geq M$. We assume a standard channel model as in (Foschini, 1996; Wolniansky *et al.*, 1998). The channel is given as an $N\times M$ matrix $\boldsymbol{C}$ with complex Gaussian random variables of mean 0 and variance 1. We use an M-QAM constellation for each transmit antenna, whose size can be varied as desired. The transmitted signal is a vector $\boldsymbol{S}_\mathrm{t}$ of size $M\times 1$ whose entries correspond to a QAM signal from each antenna. The received signal vector $\boldsymbol{S}_\mathrm{r}$ and noise vector $\boldsymbol{N}$ are of size $N\times 1$. The elements of the noise vector are zero-mean Gaussian random variables with noise density N_o. The desired target BER is BER_target. Let E_tx be the total peak power constraint at the transmit side (tx stands for transmitter with all the antennas combined).

From (Foschini, 1996; Wolniansky *et al.*, 1998), the received signal is modelled as

$$\boldsymbol{S}_\mathrm{r}=\boldsymbol{C}\cdot\boldsymbol{S}_\mathrm{t}+\boldsymbol{N}\ \ (\boldsymbol{N}\text{ is channel noise vector}). \quad (1)$$

At the detector a zero-forcing linear detector is assumed. Conceptually the detector produces an estimate of the transmitted vector, $\boldsymbol{S}_\mathrm{det}$, by the following operation

$$\boldsymbol{S}_\mathrm{det}=(\boldsymbol{C}^\dagger\boldsymbol{C})^{-1}\boldsymbol{C}^\dagger\boldsymbol{S}_\mathrm{r}\ \ (\boldsymbol{C}^\dagger\text{ is the conjugate transpose}), \quad (2)$$

which gives

$$\boldsymbol{S}_\mathrm{det}=\boldsymbol{S}_\mathrm{t}+(\boldsymbol{C}^\dagger\boldsymbol{C})^{-1}\boldsymbol{C}^\dagger\boldsymbol{N}. \quad (3)$$

Denote $[\boldsymbol{C}^\dagger\boldsymbol{C}]_{ii}^{-1}$ by $\boldsymbol{C}[i]$. For each transmit antenna with transmit power Es_i and k_i bits and constellation size $L_i=2^{k_i}$, the BER is tightly bounded according to (Winters *et al.*, 1994; Winters, 1998; Goldsmith and Chua, 1997), by

$$BER_i \leq 0.2\exp\left[\frac{-1.5}{L_i-1}\frac{Es_i}{N_\mathrm{o}}\frac{1}{\boldsymbol{C}[i]}\right]=BER_\mathrm{target}. \quad (4)$$

Rewriting the above equation provides

$$k_i=\log_2\left[1+\frac{-1.5}{\ln(5BER_\mathrm{target})}\frac{Es_i}{N_\mathrm{o}}\frac{1}{\boldsymbol{C}[i]}\right]. \quad (5)$$

Let $D_i=\dfrac{-1.5}{\ln(5BER_\mathrm{target})}\dfrac{1}{N_\mathrm{o}}\dfrac{1}{\boldsymbol{C}[i]}$. Hence $k_i=\log_2(1+D_iEs_i)$. The total sum of bits transmitted over all the antennas is $\sum_{i=1}^{M}k_i$ and the total power utilized over all the antennas is $\sum_{i=1}^{M}Es_i$. Here we seek to maximize $\sum_{i=1}^{M}k_i$ under the constraint that $\sum_{i=1}^{M}k_i$ is limited. The Lagrangian is formulated as

$$L=\sum_{i=1}^{M}k_i+\mu\sum_{i=1}^{M}Es_i, \quad (6)$$

here μ is the Lagrangian multiplier. Taking partial derivative of Eq.(6) with respect to each Es_i gives

$$\frac{\partial L}{\partial(Es_i)}=0=\frac{D_i}{(1+D_iEs_i)\ln 2}+\mu. \qquad (7)$$

This gives

$$Es_i=\frac{-1}{D_i}-\frac{1}{\mu\ln 2}, \qquad (8)$$

$\sum_{j=1}^{M}Es_j=E_{\text{tx}}$, gives $E_{\text{tx}}=-\frac{M}{\mu\ln 2}-\sum_{j=1}^{M}\frac{1}{D_j}$. This gives

$$\mu=\frac{-M}{\left(E_{\text{tx}}+\sum_{j=1}^{M}\frac{1}{D_j}\right)\ln 2}. \qquad (9)$$

Substituting Eq.(9) in Eq.(8) gives power level for each transmit antenna as

$$Es_i=\frac{-1}{D_i}+\left(E_{\text{tx}}+\sum_{j=1}^{M}\frac{1}{D_j}\right)\Big/M. \qquad (10)$$

The bits allocated to each antenna i can be found by substituting Eq.(10) into Eq.(5).

Max power to transport *R* bits for a given outage

We mentioned at the beginning of the previous section that the peak power is constrained so that a minimum rate is guaranteed for all periods outside a given percentage of outage. Any excess power is undesirable. Here we describe a technique to find the peak power necessary. We know that for each ith transmit antenna,

$$Es_i=\frac{-N_o\ln(5BER_{\text{target}})}{1.5}(2^{k_i}-1)\boldsymbol{C}[i]. \qquad (11)$$

Since each antenna on an average transports R/M bits,

$$\frac{-N_o\ln(5BER_{\text{target}})}{1.5}(2^{k_i}-1)=\frac{-N_o\ln(5BER_{\text{target}})}{1.5}(2^{R/M}-1)=T$$

is fixed.

To achieve the BER_{target}, the power level in Eq.(11) is the minimum necessary for a given $\boldsymbol{C}[i]$ at antenna i. Hence any power above this level could be used to transport the Base Layer bits. Suppose the outage probability desired is p, then the probability of outage is given by $Prob(Es_i \ge T\cdot\boldsymbol{C}[i])=p$, or $Prob(\boldsymbol{C}[i]\ge Es_i/T)=p$. Hence

$$Prob\left(\sum_{i=1}^{M}\boldsymbol{C}[i]\le\left(\sum_{i=1}^{M}Es_i\right)\Big/T\right)=p. \qquad (12)$$

The maximum power required depends implicitly on the TCBR or Base Layer bits and the statistics of the channel. It was shown in (Winters *et al.*, 1994) that $\boldsymbol{C}^{-1}[i]$ is chi-square distributed. Hence each $\boldsymbol{C}[i]$ is inverse gamma distributed with even degrees of freedom. The distribution of the summation of inverse gamma distributed random variables is unknown (Wilks, 1947; Witkovsky, 2001; 2002; Atay-Kayis and Massam, 2005; Farell, 1985; Kullback, 1934). Hence peak power required is derived from simulations and collecting the statistics of $\sum_{i=1}^{M}\boldsymbol{C}[i]$. The peak power is found from the density function of $\sum_{i=1}^{M}\boldsymbol{C}[i]$ and the value corresponds to the portion of the curve under 1~p area. Now since anything above this value occurs for only p of time, therefore the outage probability will be p.

Application layer techniques

As mentioned above, the physical layer can transmit only a certain number of bits based on maximizing channel capacity. However the physical layer, when presented with a bit stream, does not know which bits when dropped will have the lowest impact on quality, when it matches the source rate and the channel capacity. Hence a novel use of progressive Fine Grained Scalability (FGS) (van der Schaar and Hayder, 2002; Sun and Reibman, 2000; Cheng and El Zarki, 2003; 2004a; 2004b; Albanese *et al.*, 1996; van der Schaar *et al.*, 2003) encoding strategy is proposed so that the physical layer can make intelligent bit dropping choices. In FGS there are two layers: a base layer (BL), whose rate is nearly constant, and an enhancement layer (EL), whose rate is variable. Supposing the minimum QoS rate R is taken as the BL rate, one could at least guarantee the reception of BL for all non-outage periods. The remaining power in each transmission period could be used to guarantee reception of additional bits from the EL. In FGS, the bits are naturally ordered with decreasing priority. Hence the physical layer can select the bits from the beginning and drop at the end. This strategy will allow the physical layer to select the bits to be picked without knowing the semantics of the video stream. Since the physical layer technology maintains a minimum QoS for all periods outside outage, at least the base layer is guaranteed to be transmitted under BER constraints. During outage not even R bits can be transported under power constraints and therefore base layer bits will also be dropped. However the outage will be constrained to p by choosing constraint power from results in the previous section.

DEMONSTRATION OF SOLUTION

A progressive FGS coder (Microsoft Corporation, 2000; ISO-IEC/JTC1/SC92/WG11, 1993) is used which outputs a 96 kbps base layer and a variable rate enhancement layer (with an average rate of 150 kbps). The data is compared against a 240 kbps single layer encoding bit rate scheme in Fig.1. In both cases, the picture is QCIF (176×144) with a frame rate of 10 frames per second. The proposed solution performs on average 5~6 dB better.

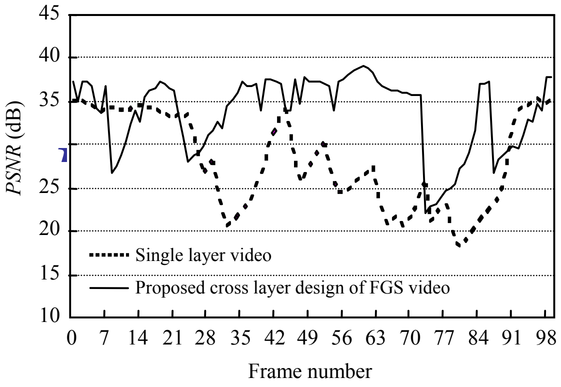

Fig.1 Performance of proposed FGS cross layer design solution

CONCLUSION

In this paper we proposed a new cross layer scheme for real-time video that satisfies a minimum QoS. We derived the solution for optimal power allocation and bit allocation to each antenna of a MIMO system. Then we introduced the usage of FGS encoding scheme to match the channel bit rate. The scalable video encoder provides the ability to truncate video without understanding the syntax of the video stream. This makes it ideal for an efficient cross layer implementation for real time video. The PSNR of the received video is improved by a wide margin.

References

Albanese, A., Blomer, J., Edmonds, J., Luby, M., Sudan, M., 1996. Priority encoding transmission. *IEEE Trans. Inform. Theory*, **42**(6):1737-1744. [doi:10.1109/18.556670]

Atay-Kayis, A., Massam, H., 2005. A Monte Carlo method for computing the marginal likelihood in nondecomposable Gaussian graphical models. *Biometrika*, **92**(2):317-335. [doi:10.1093/biomet/92.2.317]

Cheng, L., El Zarki, M., 2003. An Adaptive Error Resilient Video Encoder. Visual Communications and Image Processing.

Cheng, L., El Zarki, M., 2004a. Perceptual Quality Feedback Based Progressive Frame-level Refreshing for Robust Video Communication. Wireless Communication and Networking Conference.

Cheng, L., El Zarki, M., 2004b. PGOP: An Error Resilient Technique for Low Bit Rate and Low Latency Video Communications. Picture Coding Symposium (PCS'04). San Francisco, CA, USA.

Chuah, C.N., Kahn, J.M., Tse, D., 1998. Capacity of Multi-antenna Array Systems in Indoor Wireless Environment. IEEE GlobeCom, p.1203-1214.

Farell, R.H., 1985. Multivariate Calculation—Use of the Continuous Groups. Springer Series in Statistics.

Foschini, G.J., 1996. Layered space-time architecture for wireless communication in a fading environment when using multiple antennas. *Bell Laboratories Technical Journal*, **1**(2):41-59. [doi:10.1002/bltj.2015]

Kullback, S., 1934. An application of characteristic functions to the distribution problem of statistics. *Annals of Mathematical Statistics*, **5**:263-307.

Goldsmith, A.J., Chua, S.G., 1997. Variable-rate variable-power MQAM for fading channels. *IEEE Trans. Comm.*, **45**(10):1218-1230. [doi:10.1109/26.634685]

ISO-IEC/JTC1/SC92/WG11, 1993. Test Model 5.

Luo, W.J., El Zarki, M., 1997. Quality control for video over broadband networks. *IEEE J. Selected Areas of Communications*, **11**:1029-1039.

Microsoft Corporation, 2000. ISO/IEC 14496 (MPEG-4) Video Reference Software. Microsoft-FPDAM1-1.0-000403.

Raleigh, G.G., Cioffi, J.M., 1996. Spatio-temporal Coding for Wireless Communication. Proc. 1996 IEEE Globecom, **3**:1809-1814. [doi:10.1109/GLOCOM.1996.591950]

Raleigh, G.G., Cioffi, J.M., 1998. Spatio-temporal coding for wireless communication. *IEEE Trans. Comm.*, **46**(3):357-366. [doi:10.1109/26.662641]

Sun, M.T., Reibman, A.R., 2000. Compressed Video over Networks: Wireless Video. Marcel Dekker, New York.

van der Schaar, M., Hayder, R., 2002. Adaptive motion compensation fine-granular-scalability (AMC-FGS) for wireless video. *IEEE Transactions on Circuits and Systems for Video Technology*, **12**(6):360-371. [doi:10.1109/TCSVT.2002.800319]

van der Schaar, M., Krishnamachari, S., Choi, S., Xu, X., 2003. Adaptive cross-layer protection strategies for robust scalable video transmission over 802.11 WLANs. *IEEE J. Selected Areas of Communications*, **21**(10):1752-1763. [doi:10.1109/JSAC.2003.815231]

Wilks, S.S., 1947. Mathematical Statistics. Princeton University Press.

Winters, J.H., 1998. Smart Antenna for Wireless Systems. IEEE Personal Communications, p.23-27.

Winters, J.H., Salz, J., Gitlin, R.D., 1994. The impact of antenna diversity on the capacity of wireless communication systems. *IEEE Trans. Comm.*, **42**(4):1740-1751. [doi:10.1109/TCOMM.1994.582882]

Witkovsky, V., 2001. Computing the distribution of a linear combination of inverted gamma variables. *Kybernetika*, **37**(1):79-90.

Witkovsky, V., 2002. Exact distribution of positive linear combinations of inverted chi-square random variables with odd degrees of freedom. *Statistics & Probability Letters*, **56**:4550.

Wolniansky, P.W., Foschini, G.J., Golden, G.D., Valenzuela, R.A., 1998. VBLAST: An Architecture for Realizing Very High Data Rates over the Rich-Scattering Wireless Channel. Proc. ISSSE-98. Pisa, Italy.