Efficient Resource Management with Reduced Overhead Information

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***Abstract*— A more realistic and robust resource allocation mechanism for wireless networks is proposed which enables wireless network systems to communicate efficiently and combat harsh wireless channels. In order for a central spectrum moderator (CSM) to efficiently allocate wireless resource to wireless stations (WSTAs), overhead information is requisite. A new iterative version of the VCG (Vickrey-Clarke-Groves)-Kelly mechanism is introduced in order to reduce the amount of overhead information by appropriate selection of the initial value of bids playing an important role in convergence performance. This new mechanism uses prediction for the initial bid value for the next service interval (SI) with information of the optimal value of bids in the current SI.**

Keywords-component; VCG-Kelly, CSM, WSTA, resource allocation, mechanism, bid, optimization, linear prediction

I. INTRODUCTION

Despite the fact that wireless resources are limited, the demand for them keeps increasing. Due to this increasing demand and the scarcity of those resources, users who want to utilize wireless resources will not be truthful to report their required resources to get as much resources as they can. In order to address this ceaseless increase, many novel methods for resource allocation have been developed [1]. One of the celebrated mechanisms is the VCG mechanism [2][3][4]. In contrast to other mechanisms, the VCG mechanism takes selfish users into consideration. One of the strong points of the VCG mechanism is that truthful reporting is the dominant equilibrium strategy despite selfish users. [5] implemented the VCG mechanism under specific wireless multimedia communication system. However, there is a critical drawback in the VCG mechanism from a practical viewpoint in wireless networks. When CSM with VCG mechanism does not have information about the utility function of WSTAs, CSM necessitates overhead information of infinite dimension from WSTAs to allocate resources efficiently. Various efforts to reduce overhead data has been performed [6]-[10]. [6] and [15] proposed a new mechanism for efficient resource allocation. However, overhead information is a two dimensional signal. While [7] and [8] proposed an allocation mechanism with one dimensional bid, this mechanism was applied to one link. [9], [16], and [10] contemporary developed a novel resource allocation mechanism with one dimensional overhead signal. [9] and [16] are a more general case than [10]. [10] proposed the VCG-Kelly mechanism. Those works didn't show the practical methodologies to solve the proposed mechanisms.

In this paper, we propose a practical methodology for the VCG and VCG-Kelly mechanism. Moreover, comparison of performance between the VCG and VCG-Kelly mechanism from a practical viewpoint is performed. Furthermore, we propose a new iterative version of the VCG-Kelly mechanism. This enables the system to quickly find optimal values so that the amount of overhead data is further reduced. The organization of this paper is as follows. Section Ⅱ describes the multimedia wireless communication system which is considered in this paper. In section Ⅲ, the VCG and VCG-Kelly models are briefly introduced with practical approaches and then a comparison between the two mechanisms is performed. Section Ⅳ introduces an iterative version of the VCG-Kelly mechanism. Section Ⅴ shows the simulation results. Finally, a conclusion is drawn in section Ⅵ.

II. SYSTEM MODELS

Users (in our case, WSTAs) $N \in \mathbf{N}$ are trying to transmit their video stream by procuring transmission time and one Access Point (AP) (in our case, CSM) to manage wireless resource, time $t \in \mathbf{R}_+$, in a single hop WLAN system. We assume that a polling-based mechanism is utilized at the CSM side to allocate wireless resource to each WSTA. The CSM allocates divisible wireless resource, t_{SI} service interval (SI), to WSTAs. All WSTAs, considered selfish and non-cooperative, are competing to obtain as much time as possible. The length of t_{SI} is determined based on channel and multimedia source characteristics [11].

Figure 1 depicts the framework of our system. During every SI, each WSTA anticipates the wireless channel and video source characteristic of the next SI. With these predicted data, WSTAs try to maximize their utility function. However, they do not know how much time they can use, thus they should send appropriate overhead data to the CSM for receiving the fraction time of SI. Fig. 1 depicts the framework of our system.

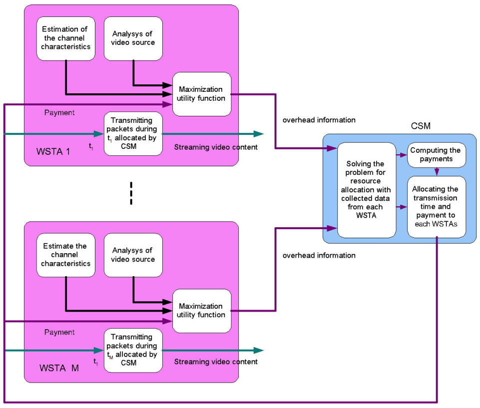

Figure 1. the framework of resource allocation mechanisms for multiuser wireless multimedia communication.

After collecting all overhead information, the CSM maximizes the sum of all WSTAs' utility functions. After maximization, the CSM computes payments which each WSTA has to pay for its resource allocation. After all computation, the CSM notifies payment to each WSTA and allocates the fraction time of SI to each WSTA.

III. VCG AND VCG-KELLY MECHANISM

A. VCG mechanism

At the CSM side, the optimization problem is as follows.

$$\text{maximize} \sum_{i \in N} \mathrm{W}_i(t_i), \quad \text{subject to} \sum_{i \in N} t_i \le t_{SI} \tag{1}$$

W_i is the reported utility function from the i^th WSTA. With these utility functions, the CSM solves the above problem. The payment equation for each WSTA is the following.

$$\sum_{j \ne i} W_j(t_j^{VCG}) - \max_{x_i = 0} \sum_{j \ne i} W_j(t_j) \tag{2}$$

CSM computes N payment equations and then transmits the results to each WSTA. With these payment and allocated time information, each WSTA solves the following problem.

$$\text{maximize} \quad U_i(t_i^{VCG}) + \sum_{i \ne j} W_j(t_j^{VCG}) - \max_{x_i = 0} \sum_{i \ne j} W_j(t_j) \tag{3}$$

U_i is the real utility function of WSTA i. If all W_i are equal to U_i, then

$$\sum_{i \in N} \mathrm{W}_i(t_i) = U_i(t_i^{VCG}) + \sum_{j \ne i} W_j(t_j^{VCG}) \tag{4}$$

This means that CSM maximizes the function of i^{th} WSTA when i^{th} USER truthfully reports its utility function ($\mathrm{W}_i = U_i$). This leads the dominant strategic equilibrium.

From the practical viewpoint, CSM does not have information about each WSTA's utility function. Thus, each WSTA has to send infinite dimensional signals about its utility function. This is not realistic. Thus, we propose one practical approach to solve this unrealistic problem.

Algorithm 1: Piecewise Linear Model

1) Each WSTA takes several tens of samples from its utility function.
2) Transmits these samples
3) CSM reconstructs each WSTA's utility function as piece-wise linear form from these samples
4) Solves the approximated version of problem which is the sum of utility functions

The approximated version:

$$\begin{aligned} &\text{maximize} \quad \sum_{i \in N} b_i \\ &\text{subject to} \quad U_i(m) + \frac{(U_i(m+1) - U_i(m))}{\Delta r_i} \times (r_i - (m-1) \times \Delta r_i) \ \ge \ b_i \\ &\qquad\qquad 1 \le i \le N, \quad 1 \le m \le L_i - 1 \\ &\sum_{i \in N} r_i \le R_{SI} \end{aligned} \tag{5}$$

[1]

B. VCG-Kelly mechanism

Centralized optimization problem of VCG mechanism for system is decentralized into two optimization problems: a network problem and a user problem. The network problem is as follows.

$$\begin{aligned} &\text{maximize} \quad \sum_{i \in N} \omega_i f_i(t_i) \\ &\text{subject to} \quad \sum_{i \in N} t_i \le t_{SI}, \quad t_i \ge 0 \quad \text{for } 1 \le i \le N \end{aligned} \tag{6}$$

ω_i is a bid from the i^{th} WSTA and $f_i(\,)$ is a surrogate function for i^{th} WSTA. We use a log function as $f_i(\,)$ because it satisfies the condition on a surrogate function [10] and PSNR is used as a utility function in our development whose shape is very similar to that of log function, thus providing a well-approximated value to the real PSNR value. The payment is defined as follows.

$$\sum_{j \ne i} \omega_j f_j(t_j^{VCGK}) - \max_{t_i = 0} \sum_{j \ne i} \omega_j f_j(t_j) \tag{7}$$

The following problem is the user's problem.

$$\Pi_i(\omega_i, \omega_{-i}) = U_i(t_i^{VCGK}) + \sum_{j \ne i} \omega_j f_j(t_j^{VCGK}) - \max_{t_i = 0} \sum_{j \ne i} \omega_j f_j(t_j) \tag{8}$$

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[1] Even though time is allocated to WSTAs, the allocate resource is considered either as time or as rate according to the utility function. The conversion of time to rate is easily computed when the information of channel bandwidth is known. In this paper, rate is used because the variable of our utility function is rate.

With special buyers' assumption [10], the VCG-Kelly mechanism has Nash Equilibrium Points (NEPs) and divisible resources are efficiently allocated at those NEPs.
In [9], a more detailed explanation is developed. VCG-Kelly mechanism requires several iterations of the following steps:

1) WSTAs compute, determine, and transmit bids.
2) With surrogate functions and collected bids, CSM solves the network problem and computes payments for each WSTA.
3) CSM sends information about allocated time and payment to each WSTA
4) With received information, WSTA performs step 1 again before arriving at a NEP.

For now, we propose a bisection method for solving the VCG-Kelly mechanism. Initial maximum value is $U_i(t_{SI})/\log(t_{SI})$ because a certain WSTA obtains at most t_{SI} and initial minimum value is zero because this means a WSTA does not participate in the game.

Algorithm 2: Bisection Method

Repeat

1) Set max and min as the maximum and minimum values which are defined above.
2) If $[\prod_i(\omega_i,\omega_{-i})]_k \ge [\prod_i(\omega_i,\omega_{-i})]_{k-1}$ at k^th iteration, then update
   min := the current bid value
   If $[\prod_i(\omega_i,\omega_{-i})]_k \le [\prod_i(\omega_i,\omega_{-i})]_{k-1}$ at k^th iteration, then update
   max := the current bid value
3) Update the bid value

$$\omega_i := \frac{\max + \min}{2}$$

Until the system approaches to a NEP.

If the difference of either allocated resources or payment values between the current and previous iteration is less than tolerance, we decide the system is at a NEP.

C. Comparison

Table I summarizes the comparison of Sample-VCG and VCG-Kelly mechanisms.

TABLE I. COMPARISON OF VCG AND VCG-KELLY

	Sample-VCG	**VCG-Kelly**
Overhead data (bits)	$N \times M \times L$	$N \times K \times L$
Accuracy	Over 90%	Around 99%
PER at one iteration	$1-(1-BER)^{L \times M}$	$1-(1-BER)^{L}$

L bits are required to represent values such as a sample from the PSNR graph or a bid. For the VCG case, each of the N WSTAs sends M samples to the CSM. For the VCG-Kelly case during K iterations, each of the N WSTAs sends one sample but not M samples because CSM uses surrogate function. In general, the longer the length of a packet, the higher the error probability becomes on the packet. This tells Sample-VCG has higher risk to error than VCG-Kelly. In addition, the VCG mechanism is vulnerable to error due to no chance to recover error by the only one iteration, while the VCG-Kelly mechanism uses iterations.

IV. PREDICTION OF BIDS

Now, we propose a new iterative version of the VCG-Kelly mechanism. This proposed method utilizes the information about the previous optimal bid values. These previous values are useful not only because the environment would not be changed for several SIs but because these values are used to predict the initial value of bids at the next SI. Well chosen initial value of bids can provide significant contributions to reduction of the amount of overhead information as well as to the rate of converge to an NEP. The newly proposed VCG-Kelly mechanism is depicted in the Fig. 2. When a WSTA starts to stream its video source, the PSNR graph is usually fixed. On the other hand, the wireless channel characteristics are dynamically changed as time goes by. This has a huge effect on the value of PSNR and bids. Thus in order to find optimal bid values quickly, the proposed scheme predicts the initial bid values with the previous optimal bid values.

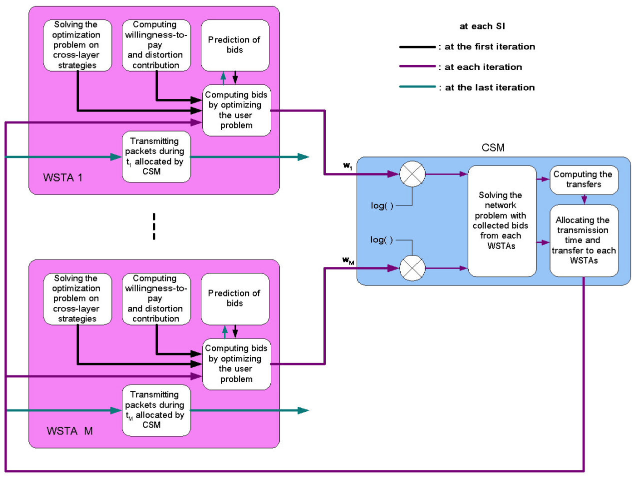

Figure 2. the framework of the iterative VCG-Kelly mechanism.

An adaptive normalized linear mean square (NLMS) error prediction method [13] is introduced as one of the prediction methods. The P^th order linear prediction is defined in (9) and (10).

$$\hat{\omega}(n+1) = \sum_{l=0}^{P-1} w(l)\omega(n-l) \tag{9}$$

where

$$\mathbf{w} = [w\ (0), w\ (1), ..., w\ (p-1)]^T$$
$$\boldsymbol{\omega}(n) = [\omega(n), \omega(n-1), ..., \omega(n-p+1)]^T \quad (10)$$

$$e(n) = \omega(n+1) - \hat{\omega}(n+1)$$
$$\mathbf{w}(n+1) = \mathbf{w}(n) + \frac{\mu e(n)\boldsymbol{\omega}(n)}{\|\boldsymbol{\omega}(n)\|^2}$$

ω represents a bid and w represents the coefficient of the predictor. e is difference between the real bid value and the predicted bid value. Different from other predictors, this predictor updates the coefficients with the information of error. Thus, the adaptive NLMS predictor does not need the autocorrelation information of the predicted value w. The performance of NLMS largely depends on the step size μ and the value of order P. These values are chosen differently as the wireless channel characteristic. Comparison of performance at several different choices for μ and P is well described in [13]. The new iterative version of the VCG-Kelly mechanism is defined as follows.

Algorithm 3: Iterative Version of VCG-Kelly Mechanism

Repeat once at each SI

1) Predict the initial value of bids with the previous optimal value of bids
2) Check the difference between the predicted bid value and the previous optimal bid value
3) Change the maximum and minimum value of algorithm 2 proportional to the difference

$$\max = w_{prd} + \alpha \times |w_{prd} - w_{prv}|$$
$$\min = w_{prd} - \alpha \times |w_{prd} - w_{prv}|$$

4) Perform VCG-Kelly mechanism with the values obtained from the above procedure.

V. SIMULATION RESULT

A. *Performance of Piecewise Linear Model*

We compared the performance between when each WSTA sent its whole utility function and when each WSTA transmitted several tens of samples of its utility function. In this simulation, we assumed that the channel bandwidth was 8 MHz, SNR is 25dB, and t_{SI} is 106 ms, which amounts to approximately one fifth of the duration of GOP. We assumed there were five WSTAs each using a different utility function. We used the DR model proposed in [14] because this model was well-suited for the average rate-distortion behavior. The DR model in [14] was given by

$$D = \frac{\mu}{R - R_0} + D_0, \quad R \geq R_0, \quad D_0 \geq 0, \quad \mu > 0 \quad (11)$$

Table Ⅱ summarized the used video sequence parameters.

TABLE II. MODEL PARAMETERS FOR VIDEO SEQUENCES

WSTA	Video Sequence	μ	D_0	R_0
1	Foreman (CIF, TL=4, 30Hz)	5232400	0	0
2	Coastguard (CIF, TL=4, 30Hz)	6329700	4.3	0
3	Mobile (CIF, TL=4, 30Hz)	38230000	1	44040
4	Foreman (QCIF, TL=4, 30Hz)	2653300	0	19614
5	Foreman (CIF, TL=4, 15Hz)	2760000	1	20720

We also assumed all video packets were organized according to importance with the size of each packet which was equal to 8KByte. Table Ⅲ depicted accuracy when WSTAs transmitted samples of their utility functions.

TABLE Ⅲ. COMPARISON OF SUM OF PSNR AND ACCURACY FOR DIFFERENT SAMPLES AND DIFFERENT BANDWIDTH

# of samples	Total PSNR (dB)	Accuracy (opt=142.282)	Total PSNR (dB)	Accuracy (opt=190.334)
10	156.455	91%	190.305	99%
20	148.23	96%	190.570	99%
50	143.498	99%	190.346	99%
100	142.357	99%	190.357	99%

In the first scenario, the bandwidth was 42.4 KHz while in the second scenario the bandwidth was 3.52 MHz. As expected, the performance with respect to the sum of total PSNR depended on the number of samples and on the bandwidth. When bandwidth was small, fewer samples resulted in lower performance because the shape of PSNR changed drastically with the amount of samples.

B. *Performance of VCG-Kelly*

In this simulation, we compared the PSNR performance of the VCG mechanism to that of the VCG-Kelly mechanism. Table Ⅳ showed the simulation result.

TABLE IV. COMPARISON OF PSNR PERFORMANCE BETWEEN VCG AND VCG-KELLY MECHANISM

	VCG	VCG-Kelly
WSTA 1	39.8179	39.5271
WSTA 2	36.1982	37.0794
WSTA 3	30.9965	30.0652
WSTA 4	42.7512	41.8885
WSTA 5	40.8063	41.3382
Total	190.57	189.90

We compared performance when there was a loss or error in the transmission of overhead information. We assumed an error occurs on overhead information of WSTA 3. Thus, CSM used a deteriorated value when it optimized the sum of all utility functions. Table Ⅴ depicted the PSNR of each WSTA and the total PSNR for both VCG and VCG-Kelly cases. As expected, the PSNR performance of the VCG-Kelly mechanism with error was very similar to that without error while the VCG mechanism worked poorly when an error occurred.

TABLE V. COMPARISON OF PSNRS WHEN ERROR OCCURS

	VCG (without error)	VCG (error)	VCG-Kelly (error)
WSTA 1	39.8179	39.9413	39.0729
WSTA 2	36.1982	36.2551	36.9734
WSTA 3	30.9965	10.0075	31.2797
WSTA 4	42.7512	43.0178	41.1391
WSTA 5	40.8063	41.0964	41.3324
Total	190.57	170.318	189.7975

The VCG mechanism used the only one iteration so the error was not recovered. However, an error on overhead data can be recovered through several iterations in the VCG-Kelly mechanism.

C. A New Iterative Version of VCG-Kelly

In this simulation, we inquired into the new iterative version of the VCG-Kelly mechanism as proposed in section Ⅳ. In order to fully examine the performance of the proposed mechanism, we forced the bandwidth of channel to randomly fluctuate. We set three scenarios: first, each WSTA set its initial bid values as fixed values, second, each WSTA chose its initial bid values randomly, and finally, each WSTA chose its initial bid value with the prediction method. Fig. 3 showed the performances of three scenarios with respect to the number of iterations required to converge to an NEP at each SI. And, table Ⅵ showed the average PSNR values of those three scenarios. For the proposed version of the VCG-Kelly case, the number of iterations to converge to an NEP was greatly reduced compared to other two schemes, as the PSNR performance was better than others (even though the difference was slight).

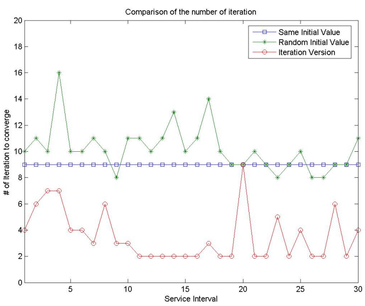

Figure 3. Comparison of the number of iterations needed to converge to a NEP per each SI.

TABLE VI. COMPARISON OF AVERAGE PSNRS

	Same Initial Value	Random Initial Value	Iteration Version
WSTA 1	42.7246	39.5203	42.8652
WSTA 2	38.1846	34.8010	38.9052
WSTA 3	32.4807	30.2588	33.9351
WSTA 4	46.1202	44.7481	45.2977
WSTA 5	43.5840	41.3627	43.9716
Total	203.0941	190.6878	204.9749

VI. CONCLUSION

In this paper, we have proposed the practical approaches to implement and solve VCG mechanisms. As shown in this paper, piecewise linear models, using several tens of samples from utility functions, are well approximated to the method using the whole utility functions. In addition, we proposed a practical method to implement the VCG-Kelly mechanism. Finally, we proposed a novel method to reduce the overhead information further. This mechanism utilizesd previous information and changed several parameters with the predicted information per SI. Additionally, this method further reduced the overhead information than the VCG-Kelly mechanism because the performance of the VCG-Kelly mechanism largely depended on the initial value of bids. In conclusion, the proposed mechanism is robust to channel error and performs like the VCG mechanism with much less overhead information.

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