Resource Management Framework for Multi-user Wireless Multimedia Using the VCG Mechanism

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***Abstract*—In this paper, we enable wireless stations (WSTAs) to proactively engage in the resource management game coordinated by a Central Spectrum Moderator (CSM). We model WSTAs as rational and selfish players competing for available wireless resources in the dynamic game. The CSM deploys a novel resource management scheme based on the Vickrey-Clarke-Groves mechanism to determine a) the amount of resource to be allocated to the various WSTAs and b) the cost associated to the allocated resources. The cost is introduced in order to discourage WSTAs from lying about their resource requirements. Each WSTA is allowed to play the resource management game by adapting its multimedia transmission strategy depending on the experienced channel conditions and derived video quality for resources. Our simulations show that using the VCG mechanism the WSTAs do not have any incentives to lie about their resource requirements as otherwise they will be severely penalized by a high cost.**

I. INTRODUCTION

Current strategies for wireless resource management include dynamic strategies such as air-fair time [1], proportional fairness [2], longest queue highest possible rate [12] etc. and static admission-control (reservation) based schemes (e.g. IEEE 802.11e [3]). However, these schemes have not proactively considered the benefits of dynamic and competitive resource management among WSTAs that relies on their ability to adapt their cross-layer strategies to changing available resources (congestion level) and varying channel conditions. Even more importantly, these existing multi-user wireless multimedia resource allocation schemes heavily rely on the users declaring their requirements in a *truthful* manner. Each WSTA will try to acquire as much of the network resources as possible (see e.g. resource management for IEEE 802.11e wireless networks [4]), unless a preemptive mechanism exists in the network. Particularly in a congested network, if some users exaggerate or lie about their resource requirements, the performance of the entire wireless network will degrade. Thus, a regulatory central system is needed that can ensure an efficient allocation of resources. This is *especially important for multimedia users* which have multiple incentives to lie about their resource requirements.

Game theory has been proposed in prior research to resolve competitive resource allocation issues for wireless networks and analyze the impact to the whole system. To address the informationally-decentralized nature of the network, pricing-based distributed resource allocation algorithms have been extensively investigated [5][6], where the price reflects the congestion in the network and the network users adjust their traffic based on the resource price. However, if the network users anticipate the effects of their actions on the network price (we refer to such users as "strategic" players), the above algorithms will lead to an inefficient allocation [15]. Most game-theoretic approaches for networking and communications focus on characterizing and analyzing different equilibrium concepts under static operating conditions. However, the application characteristics require that network entities are fundamentally redesigned to allow a dynamic utilization of resources through strategic adaptation and reconfiguration. Moreover, the relationship between the assigned resources and the gained utility is not thoroughly studied.

In this paper, we propose a novel scheme for non-collaborative multi-user wireless resource management based on Vickrey-Clarke-Groves (VCG) mechanism [7], in which WSTAs can compete for the available transmission opportunities (TXOPs). The adopted mechanism design obliges WSTAs to proactively choose the optimal cross-layer strategies and truthfully reveal their own private information. Importantly, the proposed game-theoretic approach also promotes collaboration in an indirect way through charging WSTAs based on the inconvenience they cause to other users rather than the used resources.

Specifically, each WSTA transmits to the CSM a vector of private information that quantifies its utility function (video quality) as a function of allocated time. Based on this information, the CSM allocates available transmission opportunities (TXOPs) to the WSTAs and determines the transfers to be paid by each station. The transfers are designed in such a way by the adopted game-theoretic mechanism that WSTAs have no incentive to lie about their private information even though they care only about their own utilities.

Another focus of our paper is on designing proactive cross-layer strategies for WSTAs that enable them to influence the wireless systems dynamics in such a way that their own utility is maximized. Each WSTA can then

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play the resource management game by optimally adapting its cross-layer transmission strategies and, subsequently, declaring its private information in order to maximize its own payoff. This payoff depends on both the expected utility as well as the incurred transmission cost (transfer). To effectively play the resource management game, the WSTA dynamically adapts their cross-layer strategies, based on their source characteristics and channel conditions to compete for the limited wireless resource. Note that it is not the aim of this paper to propose new joint source-channel coding or cross-layer transmission strategies. Rather, we illustrate here the proposed approach using only a limited set of transmission strategies deployed at the various layers.

The paper is organized as follows. Section II proposes a game-theoretic dynamic resource allocation framework. Section III describes the types of WSTAs. Section IV introduces VCG mechanism design in detail. Section V presents the simulation results, followed by the conclusion in Section IV.

II. FRAMEWORK OF GAME-THEORETIC DYNAMIC RESOURCE MANAGEMENT

We consider $M \in \mathbb{N}$ autonomous WSTAs that are streaming video content in real-time over a shared one-hop WLAN infrastructure. We assume that a polling-based mechanism (similar to the MAC of IEEE 802.11e [3]) is deployed by the CSM to divide the available resources among competing WSTAs every service interval (SI). The length of the SI, t_{SI}, can be determined based on the channel conditions, source characteristics and application-layer delay constraints [4].

In this paper, we propose to model the multi-user wireless communication as a non-collaborative resource management game regulated by the CSM, where the WSTAs are allowed to dynamically compete for the available TXOPs by jointly adapting their cross-layer strategies. In this non-collaborative game, the WSTAs are considered selfish (autonomous) users that solely aim at maximizing their own utilities by gathering as much resources as possible.

We assume that the channel condition experienced by WSTA i is characterized by the measured Signal to Noise Ratio (SNR) , SNR_i, which varies over time. The current state information for WSTA i is encapsulated in vector $\mathbf{x}_i$, which includes the channel condition SNR_i and the video source characteristics ξ_i, i.e. $\mathbf{x}_i = (SNR_i, \xi_i)$. In the remainder of this paper, borrowing a term from game-theory, we will refer to this vector as the WSTA's "private information". Since the private information is not known precisely prior to the actual transmission, a WSTA will need to determine its strategy for playing the resource management game based on the anticipated private information $\overline{\mathbf{x}}_i$, which includes the anticipated SNR $\overline{SNR_i}$ and the anticipated source characteristic $\overline{\xi}_i$, i.e. $\overline{\mathbf{x}}_i = (\overline{SNR}_i, \overline{\xi}_i)$.

Based on the private information, each WSTA jointly optimizes the various transmission strategies available at the different layers of the OSI stack. In this paper, we limit the cross-layer strategies to only include adapting the modulation mode at the physical (PHY) layer, the number of retransmissions per packet at the MAC layer, the packet prioritization and packet scheduling at the application (APP) layer. Let s_i represent a *cross-layer strategy* available to WSTA i, which lies in the set of feasible strategies $\boldsymbol{\mathcal{S}}_i$ for that station. The cross-layer strategy s_i is adopted in real-time by the WSTA i.

In the resource game, a *joint strategy* is defined for each WSTA $i \in \{1,...,M\}$ that consists of selecting an *anticipated cross-layer strategy* $\overline{s}_i \in \boldsymbol{\mathcal{S}}_i$ and a *revealing strategy* $\mu_i \in \boldsymbol{\mathcal{V}}_i$, where $\boldsymbol{\mathcal{V}}_i$ is the set of revealing strategies available to WSTA i. We denote the joint strategy as $\kappa_i = (\overline{s}_i, \mu_i)$, $\kappa_i \in \boldsymbol{\mathcal{S}}_i \times \boldsymbol{\mathcal{V}}_i$. The purpose of the anticipated cross-layer strategy and the revealing strategy is outlined in the subsequent paragraphs.

The anticipated cross-layer strategy $\overline{s}_i$ is computed by WSTA i *prior* to the transmission time, in order to determine what the *anticipated* benefit is in terms of utility which it can derive by acquiring available resource during the upcoming SI. Note that the anticipated cross-layer strategy $\overline{s}_i$ is proactively decided at the beginning of every SI and will not be exactly the same as the actual real-time strategy s_i adopted at transmission time. Unlike the real-time cross-layer strategy which has precise information $\mathbf{x}_i$ (e.g. the channel conditions and source characteristics, etc.), the anticipated cross-layer strategy will need to determine the modulation mode at the PHY layer, the number of retransmissions per packet at the MAC layer, the packet prioritization and scheduling at APP layer, etc. based on the anticipated private information $\overline{\mathbf{x}}_i$, which will be described in Section III.

To play the resource management game, each WSTA i needs to announce its "type", denoted as[1] $\theta_i(\overline{s}_i)$, which represents the utility that can be derived from the potentially allocated resources (TXOPs). Based on the announced types, the CSM will determine the resources allocation and transfers for the participating WSTAs. We refer to the set of possible types available to WSTA i as Θ_i.The type is defined as a nominal vector that encapsulates the anticipated private information, the anticipated cross-layer strategy $\overline{s}_i$. The type profile for all WSTAs is defined as $\theta = (\theta_1,...,\theta_M)$, with $\theta \in \boldsymbol{\Theta}$, $\boldsymbol{\Theta} = \Theta_1 \times ... \times \Theta_M$. The type vector will be described in more detail in Section III. A revealing strategy μ_i is adopted by the WSTA i to determine which type should be declared to the CSM based on the derived real type θ_i. The type of WSTA i revealed to the CSM (referred to as announced type) can be expressed as $\hat{\theta}_i = \mu_i(\theta_i)$. The

[1] Note that to simplify our notation, in the subsequent part of the paper, we omit at times the dependencies of θ_i on $\overline{s}_i, \overline{\mathbf{x}}_i, \boldsymbol{w}_i$ and refer to it simply as θ_i.

announced type profile for all WSTAs is denoted as $\hat{\theta} = (\hat{\theta}_1, ..., \hat{\theta}_M)$. In other words, the joint strategy κ_i adopted by WSTA i determines the announced type $\hat{\theta}_i$.

For the dynamic resource allocation game, the outcome is denoted as $\mathbf{T}(\hat{\theta}, \boldsymbol{\mathcal{R}})$, where $\mathbf{T} : \boldsymbol{\Theta} \times \mathbb{R}_+ \to \mathbb{R}_+^M$ is a function mapping both the announced type profile $\hat{\theta}$ and the available resource $\boldsymbol{\mathcal{R}}$ to the resource allocations. Thus, $\mathbf{T}(\hat{\theta}, \boldsymbol{\mathcal{R}}) = [t_1, ..., t_M]$, where t_i denotes the allocated time to WSTA i within the current SI and $\sum_{i=1}^{M} t_i \le t_{SI}$. Based on the dynamic resource allocation t_i and its derived type θ_i, WSTA i can derive utility $u_i(t_i, \theta_i)$. However, the utility computed at the CSM side for WSTA i is $u_i(t_i, \hat{\theta}_i)$, as this is determined based on the announced type $\hat{\theta}_i$. Note that t_i is decided by the CSM which is a function of the announce type profile $\hat{\theta}$ and the available resource $\boldsymbol{\mathcal{R}}$. Hence, note that the "real" utility derived by a WSTA and the utility that a CSM believes that the WSTA is obtaining can differ, since the CSM solely relies on the information announced by the WSTA. In our resource management game, the utility is computed not only based on the anticipated received video quality like in the conventional cross-layer design, but also on the willingness-to-pay for resources of a WSTA, $\boldsymbol{w}_i$. The transfer computed by the CSM is represented by $\boldsymbol{\tau}(\hat{\theta}, \boldsymbol{\mathcal{R}})$, where $\boldsymbol{\tau} : \boldsymbol{\Theta} \times \mathbb{R}_+ \to \mathbb{R}_-^M$ is a function of both the announced type profile $\hat{\theta}$ and the available resource $\boldsymbol{\mathcal{R}}$, and $\boldsymbol{\tau}(\hat{\theta}, \boldsymbol{\mathcal{R}}) = [\boldsymbol{\tau}_1, ..., \boldsymbol{\tau}_M]$, where $\boldsymbol{\tau}_i$ denotes the transfer that WSTA i needs to pay during the current SI. By participating in the resource allocation game, WSTA i gains the "payoff" $v_i(\hat{\theta}, \theta_i, \boldsymbol{\mathcal{R}}) = u_i(t_i, \theta_i) + \tau_i$, which is always non-negative in the VCG mechanism as shown in Section IV.

The resource management framework is proposed as shown in Figure 1. Specifically, each WSTA i performs the subsequent steps to play the resource allocation game during each SI.

1. **Derive its "type"**: Each WSTA i first estimates the anticipated private information $\bar{\mathbf{x}}_i$, including the video source characteristics and channel conditions, then determines its optimal anticipate cross-layer strategy $\bar{s}_i^{opt}$ by maximizing the anticipated received video quality under various resource allocation t_i, and finally derive the type θ_i.
2. **Reveal the type to CSM**: Based on the derived type θ_i, WSTA i determines the optimal revealing strategy μ_i^{opt} by maximizing the pay off, i.e.
$$\mu_i^{opt} = \arg\max_{\mu_i \in \mathcal{V}_i} \{u_i(t_i, \theta_i) + \tau_i\}. \qquad (1)$$
And then, the revealed type is $\hat{\theta}_i = \mu_i^{opt}(\theta_i)$. In Section IV, we prove that whenever the VCG mechanism is used, *the optimal revealing strategy* μ_i^{opt} is to reveal the real (truthful) type.
3. **Transmit video packets**: When polled by the CSM, each WSTA i determines and deploys the *optimal real-time cross-layer strategy* s_i^{opt} for video transmission that maximizes the expected received video quality.

At the same time, CSM renders the following task in the resource allocation game during each SI.

1. **Social decision**: After receiving the announced type profile $\hat{\theta}$ from the WSTAs, the CSM decides the resource allocation $\mathbf{T}(\hat{\theta})$ such that the multi-user wireless system utility (i.e. the sum of utilities of all WSTAs) is maximized.
2. **Transfer computation**: Next, it computes the transfers $\boldsymbol{\tau}(\hat{\theta})$ associated with this resource allocation to enforce the WSTA to reveal their real type truthfully.
3. **Polling WSTAs**: The CSM polls the WSTAs for packet transmission according to the allocated time.

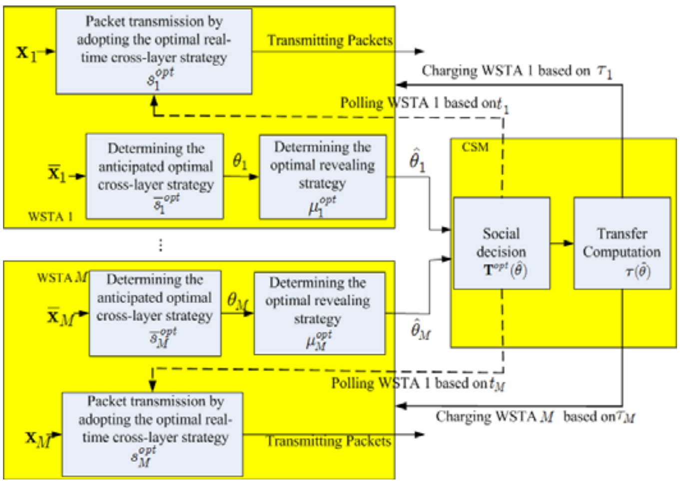


Figure 1. Mechanism design framework for the multi-user wireless video resource allocation game.

III. CROSS-LAYER STRATEGIES AND CORRESPONDING TYPES

A. Video Priority Classes

In this paper, we assume that each WSTA transmits a wavelet-based [9] pre-encoded video stream in real-time. Based on their impact on the overall distortion and their delay constraints, we divide the packets of the encoded bit stream of each Group Of Pictures (GOP) into H_i priority classes for WSTA i [4]. We assume that all the packets that are in a certain class h ($1 \le h \le H_i$) have the same quality contribution $\lambda_{i,h}$ and delay deadline. For simplicity, we also assume that the packet length L_i (which includes the various packet headers etc.) stays the same for a specific WSTA i. We assume that the classes are prioritized in decreasing order of their quality contribution, i.e. $\lambda_{i,1} > ... > \lambda_{i,H_i}$.

B. Cross-layer Strategies for Real-time Transmission

The cross-layer strategies has been comprehensively addressed in [8][12]. In this paper, we limit the cross-layer strategies to only include adapting the modulation mode at the physical (PHY) layer, the number of retransmissions per packet at the MAC layer, the packet prioritization and packet scheduling at the application (APP) layer.

Given the experienced channel condition SNR_i , the modulation mode γ_i determine the bit-error rate $e(SNR_i, \gamma_i)$ and maximum achievable bit rate $R_{\max}^{phy}(\gamma_i)$ [10]. Then, the *transmitted packet rate* is given by

$$R_i^p(SNR_i, \gamma_i, L_i) = R_{\max}^{phy}(\gamma_i)(1 - e(SNR_i, \gamma_i))^{L_i} / L_i \, . \tag{2}$$

The optimal PHY strategy γ_i^{opt} is approximately selected by maximizing the transmitted packet rate.

As shown in [8], within one GOP, the optimal real-time cross-layer strategy retransmits the most important packets until they are successfully received or their delay deadline expires. Hence, the optimal maximum number of transmissions at the MAC layer for each packet can be on-the-fly determined based on the current time and delay deadline [8].

Besides determining the optimal PHY mode selection and MAC retransmission limit, the WSTA transmits the packets starting with the most important class in a First-In-First-Output (FIFO) fashion. The packet at the head of the highest priority transmission queue is selected for the delay deadline check. If the packet's deadline is not expired, the packet is transmitted; otherwise, the packet is dropped.

C. Anticipated Cross-layer Strategy

At the beginning of the current SI, the WSTAs can only determine the anticipated optimal cross-layer strategy $\overline{s}_i^{opt}$ to play the resource allocation game since the real-time cross-layer strategies require the instantaneous private information. At this stage, the optimal PHY mode is selected similar to Eq. (2), where SNR_i is replaced with $\overline{SNR}_i$. The delay-based packet scheduling policy can also be performed based on the expected transmission time for each packet [8]. Instead of computing the optimal maximum number of transmission for each packet, we calculate the expected number of packets successfully transmitted, given a certain TXOP t_i in the current SI, as[2]

$$N_i^p = R_i^p(\overline{SNR}_i, \gamma_i^{opt}, L_i) t_i \, . \tag{3}$$

D. Determining the True and Announced Type

Based on the anticipated cross-layer strategies, we now determine the number of packets, $\eta_{i,g,h}$, to transmit in each class h during the current SI. Since the packets in the higher priority classes are transmitted first, $\eta_{i,g,h}$ can be calculated in the recursive way, as

$$\begin{aligned} \eta_{i,g,h} &= \max\{0, \min\{K_{i,g,h}^{remain}, N_i^p - \textstyle\sum_{l=1}^{h-1} \eta_{i,g,l}\}\} \\ &= R_i^p \max\{0, \min\{\frac{K_{i,g,h}^{remain}}{R_i^p}, t_i - \textstyle\sum_{l=1}^{h-1} \frac{\eta_{i,g,l}}{R_i^p}\}\} \end{aligned} \tag{4}$$

where $K_{i,g,h}^{remain}$ is the remaining packets to transmit in class h during the current SI. Thus, the utility function derived at the beginning of current SI becomes

$$u_i(t_i, \theta_i) = \textstyle\sum_{h=1}^{H} \eta_{i,g,h}\lambda_{i,h} = \sum_{h=1}^{H} (\frac{\eta_{i,g,h}}{R_i^p})(\lambda_{i,h} R_i^p) \tag{5}$$

It is easy to check that the utility function is concave over t_i .

From the computation of utility in Eqs. (4) and (5), it is sufficient for WSTA i to report to the CSM the following parameters: $\beta_{i,h} \triangleq K_{i,g,h}^{remain} / R_i^p \ (1 \le h \le H_i)$ and $\rho_{i,h} \triangleq \lambda_{i,h} R_i^p \ (1 \le h \le H_i)$, since they fully characterize the utility function over various possible resource allocations. Hence, the type of WSTA i , θ_i , becomes $\{\{\beta_{i,h}\}_{h=1,...,H_i}, \{\rho_{i,h}\}_{h=1,...,H_i}\}$. Correspondingly, the announced type $\hat{\theta}_i = \mu_i(\theta_i)$ becomes $\{\{\hat{\beta}_{i,h}\}_{h=1,...,H_i}, \{\hat{\rho}_{i,h}\}_{h=1,...,H_i}\}$ which may be different from θ_i . In this paper, we simply assume that $\hat{\rho}_{i,1} \ge .... \ge \hat{\rho}_{i,h}$ such that the utility function derived at CSM side still has the concavity property.

IV. VCG MECHANISM DESIGN

The key challenges for efficient multi-user wireless resource management are due to the informational decentralized nature of the wireless network and the strategic behaviors of the WSTAs. To overcome these challenges, we propose to adopt the VCG mechanism

In the deployed VCG mechanism, the social decision allocates the resource among the WSTAs such that the aggregated system-wide utility (i.e. the sum of utilities of all WSTAs) is maximized. Specifically, the social decision is made as follows:

$$\begin{aligned} &\mathbf{T}^{opt}(\hat{\theta}) = \arg\max_{\mathbf{T}(\hat{\theta}) = [t_1, ..., t_M]} \sum_{i=1}^{M} u_i(t_i, \hat{\theta}) \\ &s.t. \sum_{i=1}^{M} t_i \le t_{SI}, \ t_i \ge 0, \text{ for } 1 \le i \le M \end{aligned} \tag{6}$$

Then, based on the optimal resource allocation $\mathbf{T}^{opt}(\hat{\theta})$, i.e. $[t_1^{opt}, ..., t_M^{opt}]$, the CSM computes the transfers for all WSTAs as

$$\tau_i(\hat{\theta}, \boldsymbol{\mathcal{R}}) = \sum_{k \ne i} u_k(t_k^{\ opt}, \hat{\theta}_k) - \max_{\mathbf{T}_{-i}(\hat{\theta}_{-i}, \boldsymbol{\mathcal{R}})} \sum_{k \ne i} u_k(t_k, \hat{\theta}_k) \, . \tag{7}$$

where $\mathbf{T}_{-i}(\hat{\theta}_{-i}, \boldsymbol{\mathcal{R}}) = [t_1, ..., t_{i-1}, t_{i+1}, ..., t_M]$. The first term of

[2] In this paper, we relax the expected number of packets into a positive real number. And we use R_i^p to represent $R_i^p(\overline{SNR}_i, \gamma_i^{opt}, L_i)$ from now on.

Eq.(7) is the sum of aggregated utilities of the other WSTAs except WSTA i under optimal resource allocation $\mathbf{T}^{opt}(\hat{\theta},\boldsymbol{\mathcal{R}})$ in the presence of WSTA i. The second term in the summation is the maximum aggregated utility that other WSTAs can derive if WSTA i does not participate in the resource allocation game. It is clear that the first term is always less than or equals to the second term since the second one is the maximum summation of utilities for all the WSTAs except WSTA i. Hence, the transfer computed here is always negative or zero and represents the inconvenience caused to other WSTAs by WSTA i.

Due to the concavity of the utility function $u_i(t_i,\hat{\theta})$, the optimizations in Eqs. (6) and (7) can be easily solved using convex optimization techniques.

A.Dominant Strategies for Playing the Game

To prove that the optimal joint strategy $\kappa_i^{opt} = (\overline{s}_i^{opt},\mu_i^{opt})$ ($1 \le i \le M$) of a WSTA i does not depend on the other WSTAs' strategies and hence, it does not depend on the behaviors of the other WSTAs, we introduce the notion of *dominant strategy* based on [14].

Definition 1: A strategy is called a dominant strategy if it maximizes WSTA i's anticipated utility regardless of the strategies adopted by other WSTAs [14].

Based on the previous definition, we can derive the following proposition that makes the VCG mechanism suitable for determining the resource allocation for the investigated multi-user wireless video transmission case.

Proposition 1: If the resource allocation is performed by the CSM using the VCG mechanism, it is optimal for all WSTAs (in terms of their resulting payoff) to select the anticipated cross-layer strategy $\overline{s}_i^{opt}$ as well as to reveal their true type including the true willingness-to-pay attitude to the CSM ($\hat{\theta}_i = \theta_i$), regardless of the other WSTAs' strategies. In other words, the optimal joint strategy $\kappa_i^{opt} = (\overline{s}_i^{opt},\mu_i^{opt})$ is a dominant strategy. Hence, we can conclude that using the VCG mechanism, no WSTA has any incentives to lie about its type.

Proof: The payoff of WSTA i, when announcing $\hat{\theta}_i$, is

$$\begin{aligned}\upsilon_i(\hat{\theta},\theta_i,\boldsymbol{\mathcal{R}}) &= u_i(t_i^{opt},\theta_i) + \tau_i \\ &= u_i(t_i^{opt},\theta_i) + \sum_{k\neq i} u_k(t_k^{opt},\hat{\theta}_k) - \max_{\mathbf{T}_{-i}(\hat{\theta}_{-i},\boldsymbol{\mathcal{R}})} \sum_{k\neq i} u_k(t_k,\hat{\theta}_k) \\ &= \left[u_i(t_i^{opt},\theta_i) + \sum_{k\neq i} u_k(t_k^{opt},\hat{\theta}_k)\right] - \max_{\mathbf{T}_{-i}(\hat{\theta}_{-i},\boldsymbol{\mathcal{R}})} \sum_{k\neq i} u_k(t_k,\hat{\theta}_k)\end{aligned} \tag{8}$$

Note that, we expand the transfer τ_i in the first line with the computation in Eq.(7) to get the second line.

WSTA i selects the joint strategy $\kappa_i^{opt} = (\overline{s}_i^{opt},\mu_i^{opt})$ to maximize its payoff υ_i, which can be computed as

$$\begin{aligned}\kappa_i^{opt} = (\overline{s}_i^{opt},\mu_i^{opt}) &= \arg \max_{\kappa_i=(\overline{s}_i,\mu_i)\in\boldsymbol{\mathcal{S}}_i\times\boldsymbol{\mathcal{V}}_i} \upsilon_i(\hat{\theta},\theta_i,\boldsymbol{\mathcal{R}}) \\ &= \arg \max_{\kappa_i=(\overline{s}_i,\mu_i)\in\boldsymbol{\mathcal{S}}_i\times\boldsymbol{\mathcal{V}}_i} \Big\{\Big[u_i(t_i^{opt},\theta_i) + \sum_{k\neq i} u_k(t_k^{opt},\hat{\theta}_k)\Big] \\ &\qquad - \max_{\mathbf{T}_{-i}(\hat{\theta}_{-i},\boldsymbol{\mathcal{R}})} \sum_{k\neq i} u_k(t_k,\hat{\theta}_k)\Big\} \\ &= \arg \max_{\kappa_i=(\overline{s}_i,\mu_i)\in\boldsymbol{\mathcal{S}}_i\times\boldsymbol{\mathcal{V}}_i} \Big\{\Big[u_i(t_i^{opt},\theta_i) + \sum_{k\neq i} u_k(t_k^{opt},\hat{\theta}_k)\Big]\Big\} \\ &\qquad - \max_{\mathbf{T}_{-i}(\hat{\theta}_{-i},\boldsymbol{\mathcal{R}})} \sum_{k\neq i} u_k(t_k,\hat{\theta}_k)\end{aligned} \tag{9}$$

From the second line to the third line, we use the fact that the joint strategy κ_i does not affect the optimization over $\mathbf{T}_{-i}(\hat{\theta},\boldsymbol{\mathcal{R}})$ because the optimization over $\mathbf{T}_{-i}(\hat{\theta},\boldsymbol{\mathcal{R}})$ assumes that WSTA i does not exist in the network. Thus, the optimal joint strategy κ_i^{opt} is chosen by only solving the optimization

$$\arg \max_{\kappa_i=(\overline{s}_i,\mu_i)\in\boldsymbol{\mathcal{S}}_i\times\boldsymbol{\mathcal{V}}_i} \Big\{\Big[u_i(t_i^{opt},\theta_i) + \sum_{k\neq i} u_k(t_k^{opt},\hat{\theta}_k)\Big]\Big\}. \tag{10}$$

Note that $\mathbf{T}_i^{opt}(\hat{\theta},\boldsymbol{\mathcal{R}})$ is chosen by CSM after the WSTAs announce their types. We know, given the same resource allocation, the anticipated optimal cross-layer strategy $\overline{s}_i^{opt}$ derives the highest anticipated received video quality and hence the maximum anticipated utility $u_i(t_i,\theta_i)$. When the anticipated optimal cross-layer strategy and willingness-to-pay attitude are fixed, the WSTA i only has to reveal the true type determined, i.e. $\hat{\theta}_i = \theta_i$. Then, the CSM explicitly solves the following optimization

$$\max_{\mathbf{T}(\hat{\theta},\boldsymbol{\mathcal{R}})} \left[u_i(t_i,\theta_i) + \sum_{k\neq i} u_k(t_k,\hat{\theta}_k)\right], \tag{11}$$

which results in the maximum payoff for the WSTA i. Thus, the optimal joint strategy $\kappa_i^{opt} = (\overline{s}_i^{opt},\mu_i^{opt})$ is dominant, regardless of the other WSTAs' strategies and no WSTA has any incentives to lie about its type.

Importantly, while the optimal joint strategy of a WSTA is dominant, i.e. it is independent of other WSTAs' strategies, the actual resources allocated to that WSTA and its derived utility will depend on the other WSTAs' types/strategies.

In the above, we demonstrate that, using the VCG mechanism, the wireless resources are allocated efficiently among WSTAs and no WSTA has incentives to select a sub-optimal anticipated cross-layer strategy and/or lie about their own types. Herein we summarize the steps involved in the implementation of VCG mechanism in the wireless network.

The implementation of the VCG mechanism for our resource allocation is depicted in Figure 1. At the beginning of each SI, WSTA i ($1 \le i \le M$) first estimates their own anticipated private information. Next, it selects the optimal joint strategy κ_i^{opt} to maximize its own payoff υ_i, based on Eq.(9), i.e. determining the anticipated optimal cross-layer strategy and revealing strategy. Finally, the WSTA announces the real type θ_i.

The CSM allocates the resource (time) among WSTAs by solving Eq.(6) and computes the transfer as in Eq.(7) for all WSTAs. After that, the CSM polls the WSTAs according to the allocated time. When polled by the CSM, WSTA i adopts the real-time cross-layer strategy based on the private information to transmit the video data.

V. SIMULATION RESULTS

We consider five WSTAs streaming video sequences that are encoded using a 3D wavelet video codec [9]. The video applications are considered to tolerate a delay of 533 ms, which amounts to approximately one fifth of the duration of one GOP [13]. The channel conditions experienced by the five WSTAs are assumed to be similar, having an average SNR of 23dB and a variation across the various SIs of around 5dB. We also assume $t_{SI} = 106$ ms [3].

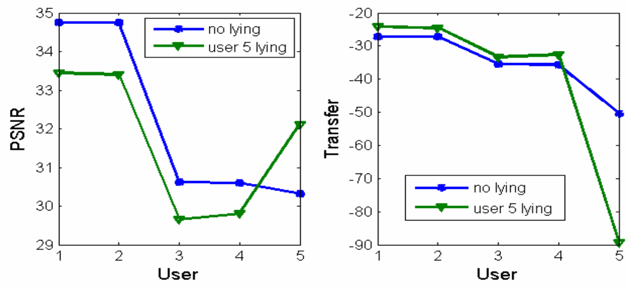
A. Assessing How the VCG Mechanism Penalizes Exaggerating (Lying) WSTAs

In this simulation result, we verify that indeed, the WSTAs will be penalized if they lie about their resource requirements by exaggerating its own type. To assess the result of the resource management game, we compare the video quality in terms of PSNR as well as the incurred transfers under two scenarios: 1) no WSTAs are lying about its type and 2) WSTA 5 is lying about its type, but other WSTAs are telling the truth. Figure 2 shows PSNRs and the corresponding transfers for the two cases. When WSTA 5 exaggerates its own type, the video quality (PSNR) for this station is improved by 1.78dB, but the transfer paid is also significantly increased by 77.1%. From the results, it can also be concluded that the exaggeration of WSTA 5 affects the performance of other WSTAs, leading to a PSNR degradation of 0.8-1.3dB. The transfers incurred by these WSTAs are only very little decreased.

From this experiment, it becomes clear that indeed, by using the VCG mechanism, the lying of WSTAs is penalized through a significantly increased transfer. We can also conclude that conventional resource allocation schemes, e.g. air-fair allocation, which heavily depend on the truthfulness of WSTAs, will result in significantly worse performance when WSTAs exaggerate their requirements, as the network coordinator does not have a mechanism to penalize WSTAs for misusing resources.

B. Impact of New WSTAs Joining the Network

In this experiment, we assess the impact that a new WSTA joining the wireless network has on the video quality performance of the existing WSTAs. At the beginning of the resource allocation game, five WSTAs exist in the network having similar setup as in Scenario A. After 0.5s, another three WSTAs (indexed WSTAs 6~8) join the network and start competing for the wireless resource. WSTAs 6~8 are assumed to have similar setups as WSTAs 1~3, respectively. Figure 3 shows the received video qualities of all the WSTAs in terms of PSNR. We notice that, when the new WSTAs join the network, the performance of the existing WSTAs gracefully degrades, which demonstrates that our proposed VCG mechanism can scale with the number of users.



(a) (b)

Figure 2. PSNRs and transfers for the various WSTAs in two cases: i) no WSTA is lying about its type and ii) only WSTA 5 is exaggerating its type. (a) experienced PSNR; (b) incurred transfers.

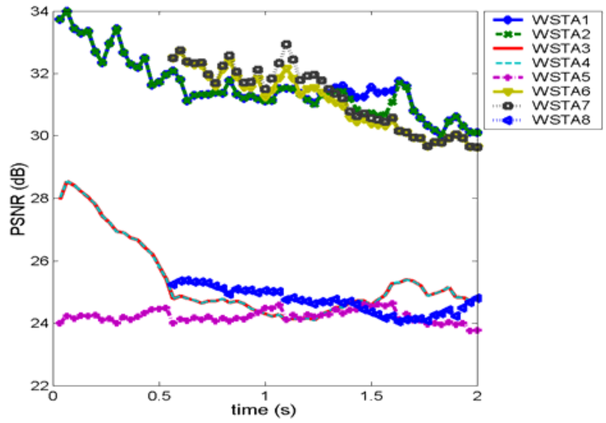


Figure 3. PSNRs of 8 WSTAs in the case where WSTAs 6~8 join into the network at time 0.5s

VI. CONCLUSIONS

In this paper we model the wireless resource allocation problem as a "game" played among competing WSTAs. For this, we adopt the VCG mechanism to ensure that resources are allocated efficiently among WSTAs. Importantly, the VCG mechanism also ensures that WSTAs truthfully declare their resource requirements by charging them for the used resources a transfer corresponding to the inconvenience they cause other users. WSTAs dynamically adapt their cross-layer strategies and correspondingly determine their announce types for playing the resource management game. Our simulations verified that using the VCG mechanism, WSTAs that are lying about their resource requirements are severely penalized by a very high transfer.

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