Noncollaborative Resource Management for Wireless Multimedia Applications Using Mechanism Design

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***Abstract*—We propose to add a new dimension to existing wireless multimedia communications systems by enabling competing stations to proactively engage in the resource management game by adapting their cross-layer transmission strategies. For this, we model wireless stations (WSTAs) as rational and selfish players competing for available wireless resources in a dynamic game. We focus on polling-based wireless LAN (WLAN) networks, where developing an efficient solution for managing the available transmission opportunities is of paramount importance. The resource allocation game is coordinated by a network moderator, which deploys a novel resource management based on the Vickrey-Clarke-Groves (VCG) mechanism to determine a) the amount of time to be allocated to the various users and b) the transmission cost associated to the allocated resources. The transmission cost is referred to in the VCG mechanism as "transfer" and depends not on the used resources, but rather on the inconvenience (in terms of utility impact) that it causes to other WSTAs. The transfer is introduced in order to discourage WSTAs from lying about their resource requirements. Importantly, this proposed dynamic resource management approach for wireless multimedia applications changes the passive way stations are currently adapting their cross-layer strategies by enabling them to selfishly influence the wireless systems dynamics by proactively adapting their packet scheduling strategies, error protection strategies, etc. Hence, each wireless station can play the resource management game by adapting its multimedia transmission strategy depending on the experienced channel conditions, derived video quality, attitude towards risk, willingness to pay for resources and available information about the wireless network. 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 transfer. We also show that deploying advanced cross-layer strategies for playing the resource management game significantly benefit the WSTAs' received video quality. The willingness-to-pay for resources is introduced to provide WSTAs a tool to gather additional resources whenever they need to transmit an important (part of a) video sequence by agreeing to pay for resources an increased cost. A novel risk-aware scheduling scheme is also proposed that provides WSTAs the ability to dynamically avoid network congestion and hence, reduce their incurred transfer.**

***Index Terms*—Cross-layer optimization, game theory, mechanism design, multiuser wireless transmission, resource management, wireless multimedia streaming.**

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I. Introduction

SIGNIFICANT contributions have been recently made to enhance the performance of wireless multimedia using cross-layer optimization (see e.g., [1], [24], [25]). However, the multimedia transmission has been often optimized in isolation, at each individual station, and does not consider its impact on the overall wireless system. Alternatively, in this paper, we propose to add a new dimension to existing multimedia communication systems by enabling WSTAs to dynamically compete for network resources by *proactively adapting* their optimized cross-layer transmission strategies, and *truthfully* declaring their time-varying resource requirements. Hence, the conventional passive optimization of transmission strategies is now modified to enable WSTAs to proactively engage in the resource management game by jointly adapting their transmission, risk attitude and willingness-to-pay for resources[1] (i.e., willingness to accept a higher transfer than normally required for a specific derived utility).

Our focus is on autonomous WSTAs that compete for wireless resources (transmission time) in order to transmit video in real-time over a shared WLAN infrastructure. In existing WLANs, the available resources are divided among competing stations through a polling-based mechanism deployed by a Central Spectrum Moderator (CSM). The CSM is often implemented at the Medium Access Control (MAC)-layer, but it can take into consideration information from other layers when determining policies to divide the available resources. Current strategies for wireless resource management include dynamic strategies such as air-fair time [2], proportional fairness [3], longest queue highest possible rate [26], etc. or static admission-control (reservation) based schemes (e.g., IEEE 802.11e [4]). An excellent review of various cross-layer wireless resource allocations from a network, MAC and physical layer perspective has been presented in [26]. Static allocation of resources is often based on worst-case, fixed traffic specifications [5] and hence, they are not able to scale with the number of WSTAs or adapt to time-varying changes in the network conditions, content characteristics or deployed cross-layer strategies. Existing dynamic solutions (e.g., [2], [3], [26]) also do not consider the impact on multimedia utility such as video quality and delay constraints [27].

Even more importantly, these existing multiuser wireless multimedia resource allocation schemes heavily rely on the

[1]Subsequently, this is referred to simply as the "willingness-to-pay."

users declaring their requirements in a *truthful* manner. Particularly in a congested network, if some users exaggerate or lie about their resource requirements, the performance of the entire wireless network will degrade. Existing resource management solutions do not prevent WSTAs from exaggerating their resource needs at the expense of competing WSTAs. In a recent IEEE Spectrum issue, Robert W. Lucky [6] argued the need for new, proactive resource management schemes that are able to prevent competing users from misusing common (shared) network resources and lying about their requirements. Importantly, he mentioned the lack of incentives for the WSTA in current wireless networks to adhere to fairness or courtesy rules: "Today we worry whether Wi-Fi will exhibit the same meltdown. There is no incentive, other than the ultimate survival of the system, for users to limit their use." Summarizing, 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 [5]), unless a preemptive mechanism exists in the network. 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. First, as the utility (multimedia quality) always increases with the transmission rate and users are not rewarded by being considerate to other users, WSTA always want to obtain the largest possible amount of time for transmission even if the resulting quality improvement is minimal. Another incentive for lying is that over-provisioning can enable WSTAs to cope with sudden variations in channel conditions or content characteristics by providing them additional opportunities for transmitting protection data. Finally, if the WSTAs are allocated sufficient resources, they have no incentive to smartly optimize their cross-layer transmission strategies, as they can achieve a relatively good video quality (e.g., through retransmitting the lost packets) even when their transmission strategies are not very efficient.

Previous research has 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. For example, in [10], the authors proposed a discrete resource-utility function aimed at maximizing the aggregate utility by dynamically assigning network resources. However, this centralized allocation method passively adjusts the allocation based on the previous observations and does not take into account the noncollaborative user behavior. Information-theoretic work on multiuser wireless resource allocation (see e.g., [26], [27]) does not consider the delay-sensitive nature of the multimedia data, the time-varying delay and importance of the various packets, the available application-layer transmission strategies to play the resource allocation game or the resulting impact on multimedia utility of the participating WSTAs.

Game theory has been proposed in prior research to resolve competitive resource allocation issues for wireless networks in a distributed and scalable manner [7], [9], [11]. In [7], a pricing mechanism is adopted for resource allocation to ensure that the sum of users' utilities is maximized. However, the users are assumed to be "price takers" (i.e., they do not anticipate the impact of their actions on the network). In [8], it has been shown that resource allocations such as those proposed in [7] suffer from an "efficiency loss," if the users exploit the fact that their actions affect the network prices. In [9], the auction mechanism was deployed for resource allocation. The optimal auction strategies for the resource-buyers are derived and the equilibrium is shown to exist. In [11], pricing schemes are introduced which can be deployed by a service provider to police the network. However, the relationship between the assigned resources and the gained utility is not thoroughly studied in [9] and [11]. Furthermore, previous research has not considered the benefits of dynamic and noncollaborative resource management among WSTAs that relies on their ability to adapt their cross-layer strategies to time-varying content characteristics, contention-levels and channel conditions.

Summarizing, even when preemptive mechanisms exist in the network to force WSTAs to adhere to existing policies for resource allocation, the problem of determining optimal utilities and strategies for allocating the transmission opportunities among various WSTAs streaming delay-sensitive multimedia still remains unsolved. For instance, defining resource allocation policies that capture the real benefit derived by users from the network constitutes an important open research area. The complexity of this problem is further exacerbated by the fact that the cross-layer optimization at each WSTA involves numerous time-varying parameters and interactions among layers, making the interactions among WSTAs and the resulting utility-resource tradeoffs very difficult to model. Moreover, WSTAs are considered autonomous entities that separately determine and optimize their deployed cross-layer strategies. Hence, another inherent property that needs to be considered when developing wireless resource allocation policies is to allow WSTAs to compete for resources by selfishly adapting their transmission strategies. Last but not least, for wireless multimedia applications, the resource management is further complicated by the delay-sensitive nature of the application, i.e., multimedia data that is received after its delay deadline does not contribute to an improved utility.

In this paper, to enforce WSTAs to declare their resource requirements truthfully and act in a socially optimal way, we adopt a tool from game-theoretic mechanism design[2] called "*transfers*"[3] through which the CSM can penalize WSTAs based on the inconvenience they cause to other users [14]. The inconvenience is quantified in terms of the utility impact they are causing other WSTAs by consuming common resources. 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.

[2]For more details on mechanism design, the interested reader is referred to [14].

[3]The transfer can be computed in terms of payments, money, computation resources or other types of resources or incentives, e.g., quotas [15].

The 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 wireless station can then 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).

In summary, our paper makes the following contributions.

1) We propose a novel scheme for noncollaborative multiuser wireless resource management based on mechanism design, in which WSTAs can compete for the available 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. In this way, WSTAs will naturally tend to distribute their requests (i.e., adapt their scheduling algorithms) over time in an efficient manner to avoid requesting resources when the network is congested and transmitting packets is expensive.
2) To effectively play the resource management game, WSTAs dynamically adapt their cross-layer strategies, based on their source characteristics and channel conditions, but also risk attitudes and willingness-to-pay, to compete for the limited wireless resource. In this way, the smartness of WSTAs will be rewarded by an improved received video quality. Note that even though the resource management is moderated by a centralized resource moderator (CSM), the various WSTAs can actively influence the CSM decision in a distributed manner by adapting their cross-layer strategies.
3) Our proposed algorithm for resource allocation provides the WSTAs the flexibility to cope with the time-varying channel characteristics, network congestion and/or importance of video sequences (or packets) by adapting their willingness-to-pay for resources (i.e., accept an increased transfer) and risk attitudes. The resource management game is played repeatedly over time (e.g., every service interval [4] in 802.11e WLANs) in order to capture the time-varying channel and video application dynamics. This leads to an improved social decision[4] for multiuser wireless resource management as opposed to existing pre-determined schemes that are difficult to enforce (because the users do not need to truthfully declare their costs and utilities) "fairness" criteria [2], [3], [12], [13].

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. Future research will include a more extensive evaluation of how various cross-layer strategies already available in the literature can be readily used or adapted in order to enable users to play the resource management game more effectively. For instance, better modulation or channel coding schemes can be used as a competitive advantage by WSTAs to derive a higher benefit (utility).

The paper is organized as follows. Section II proposes a game-theoretic dynamic resource allocation framework. Section III describes the cross-layer design for the resource allocation game and the corresponding types of WSTAs. Section IV introduces the game-theoretic mechanism design in detail for our resource allocation game as well as the associated complexity. Section V presents the simulation results, followed by the conclusion in Section VI.

The used notations are listed in Table I for the reader's convenience.

II. Resource Management for Multi-User Wireless Multimedia Communication

A. System Description

We consider $M \in \mathbb{N}$ autonomous WSTAs that are streaming video content in real-time over a shared one-hop WLAN infrastructure. These WSTAs are competing for the available wireless resources $\boldsymbol{\mathcal{R}} \in \mathbb{R}_+$, which in our system is the amount of time that can be allocated to the WSTAs. We assume that a polling-based mechanism (similar to that adopted in the QoS-enabled MAC of IEEE 802.11e [4]) is deployed by the CSM to divide the available resources among competing WSTAs. The resource management schemes implemented by the CSM can be divided in two categories. The first category performs static allocation of resources, such as in IEEE 802.11e, where, based on the pre-determined negotiated traffic specification (TSPEC) [4], [5], the CSM is polling the various WSTAs for a fixed fraction of time every service interval (SI). The length of the SI, t_{SI}, is determined based on the channel conditions, source characteristics and application-layer delay constraints [17]. The second category performs dynamic resource allocation, where the number of TXOPs allocated to each station changes every SI or group of SIs, based on the time-varying channel condition, rate or quality requirements of users [10], etc. To enable the dynamic allocation of resources, the WSTAs need to provide the CSM information about their status (e.g., their channel condition, their queue sizes, the importance of their packets, etc.) and, based on this information and available fairness policies,[5] the CSM will in real-time decide the TXOP allocation.

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 [24] 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,

[4]The term "social decision" is borrowed from mechanism design theory, see [14] for more details.

[5]As mentioned in the introduction, several fairness policies have been already proposed in the literature for multiuser wireless resource allocation. See, e.g., [3], [12], [13] for more details.

TABLE I
NOTATIONS

Notation	Description	Notation	Description
M	The number of WSTAs	$\boldsymbol{\mathcal{R}}$	The available wireless resource
t_{SI}	The length of service interval	SNR_i	Signal to Noise Ratio of WSTA i [5]
$\overline{SNR}_i$	Anticipated Signal to Noise Ratio	ξ_i	The source characteristics
$\overline{\xi}_i$	The anticipated source characteristics	$\mathbf{x}_i$	Private information
$\overline{\mathbf{x}}_i$	The anticipated private information	$Delay(t_i, s_i, \mathbf{x}_i)$	The delay incurred by $(t_i, s_i, \mathbf{x}_i)$
$\mathbf{T}$	The resource (time) allocation	t_i	The resource (time) allocated to WSTA i
s_i	The real-time cross-layer strategy	$\overline{s}_i$	The anticipated cross-layer strategy
s_i^{opt}	The optimal real-time cross-layer strategy	$\overline{s}_i^{opt}$	The optimal anticipated cross-layer strategy
$\boldsymbol{w}_i$	The willingness-to-pay vector	$\boldsymbol{\mathcal{V}}_i$	The set of available revealing strategies
$\boldsymbol{\mathcal{S}}_i$	The set of available cross-layer strategies	κ_i	Joint strategy
μ_i	The revealing strategy	$\boldsymbol{\mathcal{S}}_i \times \boldsymbol{\mathcal{V}}_i$	The joint strategy set
μ_i^{opt}	The optimal revealing strategy	$Delay_i^{\max}$	The maximum delay deadline
κ_i^{opt}	The optimal joint strategy	$\hat{\theta}_i$	The announced type
$u_i(t_i, s_i, \mathbf{x}_i)$	The utility gained in the conventional cross-layer design	$u_i(t_i, \hat{\theta}_i)$	The utility gained in the game-theoretic cross-layer design
θ_i	The type	θ	The type profile of all the WSTAs
Θ_i	The set of possible types	$\boldsymbol{\tau}$	The transfers to all the WSTAs
$\boldsymbol{\tau}_i$	The transfer (payment for allocated resources)	v_i	The payoff
$\boldsymbol{\Theta}$	The set of possible type profiles for all the WSTAs	$\mathbf{T}_{-i}$	The resource allocation when WSTA i is not in the network
$\hat{\theta}_{-i}$	The announced type profile except WSTA i	H_i	The number of priority class per GOP
L_i	Packet length	$Delay_{i,g,h}$	The delay deadline of class h of GOP g
$K_{i,g,h}$	The number of packets of class h of GOP g	γ_i	The modulation mode
$\lambda_{i,h}$	The quality contribution of each packet in class h per GOP	$P_{i,g,h,k}^{succ}$	The probability that the k -th packet of class h of GOP g is successfully received
$I_{i,g,h,k}$	The indicator for the k -th packet of class h of GOP g	$\overline{Q}_{i,g}^{rec}(t_i)$	The expected received video quality of GOP g in the current SI
$\eta_{i,g,h}$	The number of packet of class h of GOP g remaining for transmission	$Time_{i,g,h,k}^{tr}$	The transmission time of the k -th packet of class h of GOP g
$\boldsymbol{\Upsilon}_i$	The set of available transmission modes	$e(SNR_i, \gamma_i)$	The bit error rate
$R_{\max}^{phy}(\gamma_i)$	The maximum achievable bit rate	$R_i^p(SNR_i, \gamma_i, L_i)$	The expected packet rate
$n_{i,g,h,k}^{\max}$	The maximum number of transmission of the k -th packet of class h of GOP g	$\Delta t_{i,g,h,k}^{packet}$	The average transmission duration of the k -th packet of class h of GOP g
$\Delta t_{i,g+1}^{risk}$	the time prior to the maximum delay deadline in GOP g that the packets in GOP $g+1$ start to be transmitted	$n_{i,g,h,k}^{\max,opt}$	The optimal maximum number of transmission of the k -th packet of class h of GOP g
$P_i(SNR_i, \gamma_i, L_i)$	The packet loss probability	γ_i^{opt}	The optimal modulation mode
N_i^p	The expected number of packets successfully transmitted	$\overline{Time}_{i,g,h,k}^{tr}$	The average transmission time of the k -th packet of class h of GOP g
$\omega_{i,h}$	The willingness-to-pay for priority class h	H_i^{tr}	The maximum number of transmitted priority classes
$\rho_{i,h}$	The utility gain per unit time for class h	$\beta_{i,h}$	Transmission duration for the class h
$\hat{\rho}_{i,h}$	Announced utility gain per unit time for class h	$\hat{\beta}_{i,h}$	Announced transmission duration for the class h
$u^{sys}(\mathbf{T}, \hat{\theta})$	The aggregated system utility	t_i^{opt}	The optimal resource allocation to WSTA i
$\mathbf{T}^{opt}$	The optimal resource allocation		

In this notation table, the subscript i of the symbol represents WSTA i.

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.

B. Conventional Cross-Layer Design

In the static resource allocation scenarios, the resource allocation is represented by the time allocation vector $\mathbf{T}(\boldsymbol{\mathcal{R}}) =$

$[t_1,\ldots,t_M] \in \mathbb{R}_+^M$ where t_i $(0 \le t_i \le_{SI})$ denotes the allocated time to WSTA i and $\sum_{i=1}^M t_i \le t_{SI}$. Given a static time allocation, and the WSTA's specific constraints (e.g., application layer delay constraints), the cross-layer design problem has been formulated as an optimization with a certain objective (e.g., maximize goodput, minimize consumed power) based on which the optimal joint strategy across the multiple OSI layers is selected. 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. Then, given the private information $\mathbf{x}_i$ and the predetermined time allocation t_i, a cross-layer strategy s_i results in the utility $u_i(t_i,s_i,\mathbf{x}_i)$ which, for video streaming application, represents here the anticipated received video quality in terms of PSNR. Hence, the optimal cross-layer strategy can be found as

$$s_i^{opt} = \arg\max_{s_i\in\boldsymbol{\mathcal{S}}_i} u_i(t_i,s_i,\mathbf{x}_i)$$
$$s.t.\ Delay(t_i,s_i,\mathbf{x}_i) \le Delay_i^{\max}. \quad (1)$$

In the above formulation, $Delay_i^{\max}$ represents the delay constraint for the particular video transmitted by WSTA i and $Delay(t_i,s_i,\mathbf{x}_i)$ represents the delay incurred by the cross-layer strategy s_i for the specific private information $\mathbf{x}_i$ and resource allocation t_i. However, as mentioned before, since the channel conditions, video characteristics, number of participating WSTAs or even the user desired utility vary over time, the conventional cross-layer optimization described above does not exploit the network resources efficiently and hence, does not provide adequate QoS support for multimedia transmission [1], [24], especially when the network is congested. Also, importantly, the WSTA can untruthfully declare (exaggerate) its resource requirements during the initialization stage in order to obtain a longer transmission time t_i. Thus, in existing wireless networks, there is no mechanism available to prevent the WSTA from lying about the required t_i.

C. Proposed Game-Theoretic Dynamic Resource Management

To eliminate the abovementioned limitations for multiuser wireless multimedia transmission, we enable WSTAs to dynamically acquire wireless resources depending on the desired utility, their available cross-layer strategies and private information. We propose to model the multiuser wireless communication as a noncollaborative 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 as well as their willingness-to-pay and risk attitude. In this noncollaborative game, the WSTAs are considered selfish (autonomous) users that solely aim at maximizing their own utilities by gathering as much resources as possible.

To prevent the WSTAs from misusing the available resources, the CSM adopts a tool from mechanism design, referred to as *transfer*, to penalize the WSTAs from exaggerating their resource requirements. Specifically, in this paper, we use the Vickrey-Clarke-Groves (VCG) mechanism [14], [18], [28] to implement and enforce the "*rules*" of the resource allocation game. In the VCG mechanism, the resource allocation is based on a "social decision," which maximizes the aggregated multiuser wireless system utility. To encourage the WSTAs to work in this social optimal way, the CSM charges each WSTA a transfer corresponding to the inconvenience it causes to other WSTAs. In our noncollaborative wireless network, the inconvenience caused by a WSTA is quantified as the utility penalty (drop) that the competing WSTAs incur to other WSTAs due to the participation (resource usage) of that WSTA in the resource management game. In our formulation, the performance of each WSTA will depend on the private information, the adopted cross-layer strategy, but also on the WSTA willingness-to-pay for resources. The willingness-to-pay, denoted as $\boldsymbol{w}_i$, will affect the ability of WSTA i to transmit more or less video data during the current SI, by accepting to pay a larger/lower transfer. In Section III-D, we discuss in detail how the willingness-to-pay $\boldsymbol{w}_i$ affects the strategy with which the WSTA plays the resource game and its derived utility and incurred transfer. The details of the VCG mechanism deployed at the CSM are given in Section IV.

The implementation of the resource allocation game is depicted pictorially in Fig. 1. In the resource game, a *joint strategy* is defined for WSTA i 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. The reason for this is that the strategy for playing the game also depends on the WSTA's anticipated private information $\overline{\mathbf{x}}_i$. Unlike the real-time cross-layer strategy which has precise information about $\mathbf{x}_i$, 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-C.

To play the resource management game, each WSTA i needs to announce its "type" denoted as[6] $\theta_i(\overline{s}_i,\overline{\mathbf{x}}_i,\boldsymbol{w}_i)$, 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 $\overline{\mathbf{x}}_i$, the anticipated cross-layer strategy $\overline{s}_i$, as well as the willingness-to-pay $\boldsymbol{w}_i$ for resources (transfers). The type profile for all WSTAs is defined as $\theta = (\theta_1,\ldots,\theta_M)$, with $\theta \in \boldsymbol{\Theta}$, $\boldsymbol{\Theta} =$

[6]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.

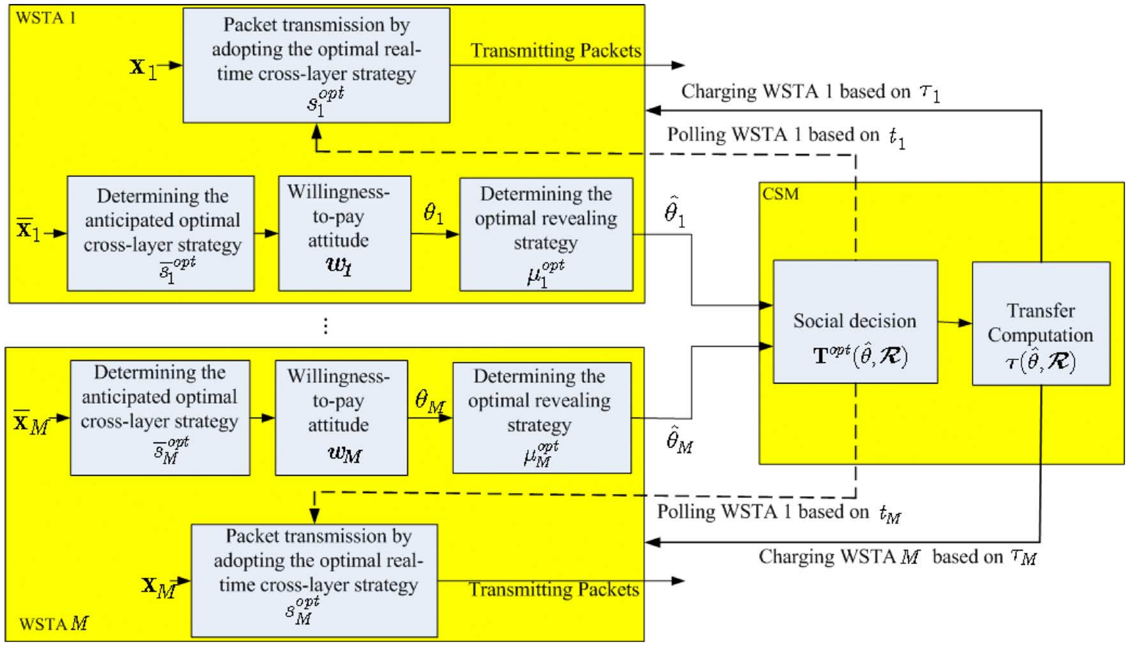

Fig. 1. Mechanism design framework for the multiuser wireless video resource allocation game.

$\Theta_1 \times \ldots \times \Theta_M$. The type vector will be described in more detail in Section III-D. 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 announced type profile for all WSTAs is denoted as $\hat{\theta} = (\hat{\theta}_1, \ldots, \hat{\theta}_M)$. In other words, the joint strategy κ_i adopted by WSTA i determines the announced type $\hat{\theta}_i$, i.e., $\hat{\theta}_i = \kappa_i(\overline{\mathbf{x}}_i, \boldsymbol{w}_i) = \mu_i(\theta_i(\overline{s}_i, \overline{\mathbf{x}}_i, \boldsymbol{w}_i))$.

For the dynamic resource allocation game, the outcome is denoted as $\mathbf{T}(\hat{\theta}, \mathcal{R})$, where $\mathbf{T} : \boldsymbol{\Theta} \times \mathbb{R}_+ \rightarrow \mathbb{R}_+^M$ is a function mapping both the announced type profile $\hat{\theta}$ and the available resource $\mathcal{R}$ to the resource allocations. Thus, $\mathbf{T}(\hat{\theta}, \mathcal{R}) = [t_1, \ldots, t_M]$, where t_i denotes the allocated time to WSTA i within the current SI and $\sum_{i=1}^{M} t_i \leq t_{SI}$. 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 $\mathcal{R}$. 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 $\tau(\hat{\theta}, \mathcal{R})$, where $\tau : \boldsymbol{\Theta} \times \mathbb{R}_+ \rightarrow \mathbb{R}_-^M$ is a function of both the announced type profile $\hat{\theta}$ and the available resource $\mathcal{R}$, and $\tau(\hat{\theta}, \mathcal{R}) = [\tau_1, \ldots, \tau_M]$, where τ_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" $\upsilon_i(\hat{\theta}, \theta_i, \mathcal{R}) = u_i(t_i, \theta_i) + \tau_i$, which is always nonnegative in the VCG mechanism [14].

In summary, we propose to implement the following dynamic, game-theoretic resource allocation at the CSM side during each SI.

1) **Social decision**: After receiving the announced type profile $\hat{\theta} = (\hat{\theta}_1, \ldots, \hat{\theta}_M)$ from the WSTAs, the CSM decides the resource allocation $\mathbf{T}(\hat{\theta}, \mathcal{R})$ such that the multiuser wireless system utility (i.e., the sum of utilities of all WSTAs) is maximized.
2) **Transfer Computation**: Next, it computes the transfers $\tau(\hat{\theta}, \mathcal{R})$ 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.

At the WSTAs side, the subsequent steps are performed by WSTA i in order to play the resource management game.

1) **Private information estimation**: Each WSTA i estimates the anticipated private information $\overline{\mathbf{x}}_i$, which includes the anticipated video source characteristics $\overline{\xi}_i$ and channel conditions in terms of $\overline{SNR}_i$.
2) **Selection of optimal joint strategy and corresponding "type"**: Based on the private information, WSTA i determines the optimal joint strategy to play the resource allocation game, i.e.

$$\begin{aligned} \kappa_i^{opt} &= \left(\overline{s}_i^{opt}, \mu_i^{opt}\right) \\ &= \underset{\kappa_i=(\overline{s}_i, \mu_i) \in \mathcal{S}_i \times \mathcal{V}_i}{\arg\max} \ \upsilon_i(\hat{\theta}, \theta_i, \mathcal{R}) \\ &= \underset{\kappa_i=(\overline{s}_i, \mu_i) \in \mathcal{S}_i \times \mathcal{V}_i}{\arg\max} \ \{u_i(t_i, \theta_i) + \tau_i\} \\ & \quad s.t.\ Delay(t_i, \theta_i) \leq Delay_i^{\max}. \end{aligned} \tag{2}$$

Note that the WSTA i cannot explicitly solve the above optimization problem, since both the resource allocation t_i and the transfer τ_i depend on the announced types of the other WSTAs, which are not known by this station.

However, in Section IV, we prove that whenever the VCG mechanism is used, *the optimal joint strategy* can be simply determined by first proactively selecting *the anticipated optimal cross-layer strategy* $\overline{s}_i^{opt}$ that maximizes the anticipated received video quality without considering the impact of the other WSTAs. Then, based on this, *the optimal revealing strategy* μ_i^{opt} through which the real (truthful) type (including willingness-to-pay attitude) is revealed is determined, i.e., $\hat{\theta}_i = \mu_i^{opt}(\theta_i) = \theta_i$. The details of the anticipated cross-layer strategy, revealing strategy and type computation are presented in Section III.

3) **Reveal the type to CSM**: The determined type $\hat{\theta}_i$ is declared by each WSTA to the CSM.
4) **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 anticipated received video quality. This cross-layer strategy is determined as discussed in Section III-B.

Note that while the transfers are computed for each WSTA during every SI, the CSM can communicate and charge the WSTA the incurred (cumulative) transfer every couple of SIs. The precise details of the charging mechanism and the protocol used for this are beyond the scope of this paper. For instance, a mechanism that can be used for charging WSTAs can be found in [16].

Summarizing, to play the resource management game, WSTAs deploy three different types of strategies at different stages of the transmission: the anticipated optimal cross-layer strategies and the revealing strategies (prior to the actual transmission, in order to determine the announced type) and the optimal real-time cross-layer strategy (in real-time, during the actual transmission). These various strategies will be described in detail in the next section.

III. Proactive Cross-Layer Strategies for Playing the Resource Management Game

To decide the optimal joint strategies for playing the dynamic resource allocation game, the WSTAs need to first determine the anticipated optimal cross-layer strategy by considering the anticipated private information. Subsequently, based on the anticipated optimal cross-layer strategy and willingness-to-pay for resources, each WSTA determines its own type and the utility for various time allocations. In current wireless video transmission systems, the real-time cross-layer strategy is adopted on-the-fly to optimize the anticipated received video quality, as shown in (1). However, in our resource allocation game, each WSTA has to determine the anticipated optimal cross-layer strategy that maximizes its received anticipated video quality at the beginning of every SI. The anticipated optimal cross-layer strategy is computed *before* transmission, in order to decide the strategy (type) for playing the game. Note that the anticipated cross-layer strategy may differ from the real-time cross-layer strategy that the WSTA will actually deploy at transmission time, when it is polled by the CSM. However, the anticipated cross-layer strategy and real-time cross-layer strategy will appertain to the same strategy set $\boldsymbol{\mathcal{S}}_i$.

The section is organized as follows. In Section III-A, we present a strategy for prioritizing the video packets into multiple classes. In Section III-B, we discuss how WSTAs can optimize their cross-layer strategies at transmission time. In Section III-C, we determine how WSTAs can anticipate this optimal cross-layer strategy that will be used at transmission time. Finally, in Section III-D, the type for each WSTA and the corresponding utility are derived based on the anticipated cross-layer strategy.

A. Video Priority Classes

In [19], [20], it has been shown that partitioning the packets into different priority classes and correspondingly adjusting the transmission strategies for each class can significantly improve the overall received quality and provide graceful degradation as congestion levels and channel conditions are changing. In this paper, we assume that each WSTA transmits a pre-encoded video stream in real-time to another WSTA over a one-hop wireless infrastructure. Based on their impact on the overall distortion and their delay constraints, we divide the packets of each encoded video stream into several priority classes. For compressing the video, we adopt a 3-D wavelet codec that uses a spatio-temporal wavelet transform followed by embedded coding [21]. However, note that this coder is simply used for illustration purposes and the proposed framework can be applied using any alternative video coding scheme (e.g., a hybrid video coder such as MPEG-2, MPEG-4 or H.264). As in [20], we determine the priority classes by jointly considering the contribution of the packets to the reconstructed video quality and their delay deadlines. We assume that all the packets corresponding to a specific Group Of Pictures (GOP) that are in a certain class have the same quality contribution 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. The number of priority classes for WSTA i equals H_i and the number of packets in class h $(1 \leq h \leq H_i)$ for GOP g equals $K_{i,g,h}$.

Summarizing, each packet k $(1 \leq k \leq K_{i,g,h})$ of class h in GOP g is associated with the following parameters: the packet length L_i (in bits), the delay deadline $Delay_{i,g,h}$ and the quality contribution $\lambda_{i,h}$ (see [20] for more details). The quality contribution $\lambda_{i,h}$ depends on the underlying video characteristics, encoding parameters, etc. and typically increases with the importance or distortion impact of the packet. We assume that the classes are prioritized in decreasing order of their quality contribution, i.e., $\lambda_{i,1} > \lambda_{i,2} > \ldots > \lambda_{i,H_i}$. Due to the hierarchical temporal structure deployed in 3-D wavelet video coders, as shown in [20], [21], the packets with the largest quality contribution are scheduled first for transmission. Hence, in this paper, we also assume $Delay_{i,g,1} \leq \ldots \leq Delay_{i,g,H_i}$.

B. Cross-Layer Design for Real-Time Transmission

The real-time cross-layer strategy is chosen on-the-fly such that the received video quality is optimized. Let $I_{i,g,h,k}$ be an indicator function which is equal to 1, when the kth packet in class h of GOP g of WSTA i is received successfully, and 0 otherwise. The probability that $I_{i,g,h,k}$ equals to 1 is denoted as $P_{i,g,h,k}^{succ}$. Let $\eta_{i,g,h}$ $(0 \leq \eta_{i,g,h} \leq K_{i,g,h})$ be the number of packets of class h of GOP g remaining in the transmission queue at the beginning of the current SI.

The anticipated received video quality[7] of WSTA i during the current SI,[8] assuming a certain time allocation t_i, can be computed as

$$\overline{Q}_{i,g}^{rec}(t_i) = \sum_{h=1}^{H_i} \sum_{k=K_{i,g,h}-\eta_{i,g,h}+1}^{K_{i,g,h}} P_{i,g,h,k}^{succ} \lambda_{i,h}. \quad (3)$$

Then, the optimal real-time cross-layer strategy can be determined in real-time to maximize the received video quality as

$$\begin{aligned} s_i^{opt} &= \arg\max_{s_i \in \boldsymbol{\mathcal{S}}_i} \overline{Q}_{i,g}^{rec}(t_i) \\ s.t.\ & I_{i,g,h,k} \cdot Time_{i,g,h,k}^{tr} \leq Delay_{i,g,h}, \text{ for all } h, k, \end{aligned} \quad (4)$$

where $1 \leq h \leq H_i$, $K_{i,g,h} - \eta_{i,g,h} + 1 \leq k \leq K_{i,g,h}$, and $Time_{i,g,h,k}^{tr}$ is the current transmission time for the kth packet in class h of GOP g of WSTA i. In the following, we illustrate how the optimal real-time cross-layer strategy is determined.

1) Modulation Mode at PHY Layer and Retransmission Limit at MAC Layer: Let $\gamma_i \in \boldsymbol{\Upsilon}_i$ denote the PHY layer modulation mode adopted by WSTA i, and $\boldsymbol{\Upsilon}_i$ be the set of available PHY modes for WSTA i. Given the experienced channel condition SNR_i, the modulation modeγ_i determine the bit-error rate $e(SNR_i, \gamma_i)$ [22]. Then, the packet loss probability is given by

$$P_i(SNR_i, \gamma_i, L_i) = 1 - (1 - e(SNR_i, \gamma_i))^{L_i}. \quad (5)$$

The maximum achievable bit rate $R_{\max}^{phy}(\gamma_i)$ can be determined by the specific modulation mode γ_i [22]. At the MAC layer, given the packet loss rate in (5), the *transmitted packet rate* can be computed as

$$R_i^p(SNR_i, \gamma_i, L_i) = \frac{R_{\max}^{phy}(\gamma_i)}{L_i} (1 - P_i(SNR_i, \gamma_i, L_i)). \quad (6)$$

Given the delay deadline $Delay_{i,g,h}$ of the packet, the maximum number of transmissions $n_{i,g,h,k}^{\max}$ (i.e., the maximum retransmission limit plus one) for a packet can be determined as it will be shown later in this section. Then, the probability that this packet is successfully received, i.e., $I_{i,g,h,k} = 1$, becomes

$$P_{i,g,h,k}^{succ} = 1 - (P_i(SNR_i, \gamma_i, L_i))^{n_{i,g,h,k}^{\max}} \quad (7)$$

and the average transmission duration for the packet is given by

$$\Delta t_{i,g,h,k}^{packet} = \frac{L_i}{R_{\max}^{phy}(\gamma_i)} \frac{1 - (P_i(SNR_i, \gamma_i, L_i))^{n_{i,g,h,k}^{\max}}}{1 - P_i(SNR_i, \gamma_i, L_i)}. \quad (8)$$

Following a similar approximation as in [5], [20], the above average duration becomes:

$$\Delta t_{i,g,h,k}^{packet} = \frac{L_i}{R_{\max}^{phy}(\gamma_i)} \frac{1}{1 - P_i(SNR_i, \gamma_i, L_i)}. \quad (9)$$

[7]As before, we use a bar above the video quality metric to indicate that this is the expected received quality and not the actual quality derived by the WSTA at transmission time.

[8]This optimization assumes that, during the current SI, only the packets in GOP g are transmitted. When the length of SI is small, this assumption is reasonable.

The optimal PHY strategy is selected to minimize the average transmission duration per packet, such that a larger number of packets can be transmitted and the received video quality (based on (3)) is maximized. Thus, choosing the optimal PHY mode can simply be done by maximizing the effective packet rate, since

$$\begin{aligned} \gamma_i^{opt} &= \arg\min_{\gamma_i \in \Upsilon_i} \left\{ \Delta t_{i,g,h,k}^{packet} \right\} \\ &= \arg\max_{\gamma_i \in \Upsilon_i} \left\{ \frac{R_{\max}^{phy}(\gamma_i)}{L_i} (1 - P_i(SNR_i, \gamma_i, L_i)) \right\} \\ &= \arg\max_{\gamma_i \in \Upsilon_i} \left\{ R_i^p(SNR_i, \gamma_i, L_i) \right\}. \end{aligned} \quad (10)$$

As shown in [20], within one GOP, the optimal real-time cross-layer strategy retransmits the most important packets until their delay deadline expires. With the prioritization in the APP layer described in Section III-A, the optimal maximum number of transmissions for a specific packet (given the current transmission time $Time_{i,g,h,k}^{tr}$) can be computed in real-time as

$$n_{i,g,h,k}^{\max,opt} = \left\lfloor \frac{R_{\max}^{phy}\left(\gamma_i^{opt}\right)\left(Delay_{i,g,h} - Time_{i,g,h,k}^{tr}\right)}{L_i} \right\rfloor. \quad (11)$$

2) Delay-Based and Risk-Aware Packet Scheduling Strategies at APP Layer: Besides determining the optimal PHY mode selection and MAC retransmission limit, the WSTA needs to determine the scheduling of the video packets in the different priority classes. For this, besides the conventional delay-based packet scheduling, we introduce a risk-aware packet scheduling scheme which enables WSTAs to reduce their "risk" of loosing the higher priority packets by transmitting them prior to other packets that have an earlier deadline but have lower priority.

The delay-based packet scheduling transmits the packets starting with the most important class in a First-In-First-Output (FIFO) fashion. When the WSTA is polled, 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. As proven in [20], the optimal delay-based scheduling is to transmit the packet until it is received or expired. However, this scheduling does not consider possible future changes in the channel condition. For example, when the time allocated to the WSTA is limited (e.g., because the network is congested) or when the experienced channel conditions are bad, the important packets from subsequent GOPs should be transmitted earlier, even if the packets with a low priority (i.e., with limited distortion contributions) in the current GOP are not expired.

We refer to this new packet scheduling as risk-aware scheduling, which adaptively and proactively determines the scheduling time for the packets across different GOPs. For the packets within one GOP, the risk-aware scheduling also adopts the FIFO policy. However, the important packets in the next GOP can be transmitted prior to the lower priority packets in the current GOP, even if these are not expired. The risk-aware scheme is advantageous when the channel is very congested because it can guarantee that the higher priority packets in each GOP are received (and hence, at least the minimum video quality is guaranteed for the WSTA) instead of transmitting the lower priority

TABLE II
RISK-AWARE PACKET SCHEDULING FOR WSTA i

Initialization: Set the current time t_{cur} ,determine the first packet to be transmitted, i.e. specify k, h, g .
Repeat:
If $t_{cur} \geq Delay_{i,g,H_i} - \Delta t_{i,g+1}^{risk}$, $g \Leftarrow g+1$, $h \Leftarrow 1$, $k \Leftarrow 1$
else $Time_{i,g,h,k}^{tr} \Leftarrow t_{cur}$;
if $Time_{i,g,h,k}^{tr} \geq Delay_{i,g,h}$, $k \Leftarrow k+1$; // go to next packet
if $k > K_{i,g,h}$, $k \Leftarrow 1$, $h \Leftarrow h+1$; // go to next class
if $h > H_i$, $h \Leftarrow 1, g \Leftarrow g+1$; // go to next GOP
end
end
end
end
Determine the retransmission limit $n_{i,g,h,k}^{\max,opt}$ and the PHY mode γ_i^{opt} ; transmit the packet.
Update the current time t_{cur} .
Until: WSTA i is not polled or the transmission queue is empty.

packets in the current GOP. Thus, the risk-aware packet scheduling will need to adapt the risk based on the network congestion and channel conditions.

Formally, we define $\Delta t_{i,g+1}^{risk}$ as the time prior to the maximum delay deadline in GOP g that the packets in GOP $g+1$ start to be transmitted. When the current time t_{cur} is greater than the threshold $(Delay_{i,g,h} - \Delta t_{i,g+1}^{risk})$, the remaining packets in GOP g are discarded and the packets in GOP $g+1$ are scheduled to be transmitted. Otherwise, the remaining packets in GOP g are transmitted in a FIFO fashion. Note that the delay-based scheduling is a particular case of risk-aware scheduling with $\Delta t_{i,g+1}^{risk} = 0$. The risk-aware packet scheduling algorithm is presented in Table II. The time $\Delta t_{i,g+1}^{risk}$ can be computed based on the video rate requirement, the private information as well as the risk attitude of the WSTA for playing the game. It is worth to note that $\Delta t_{i,g+1}^{risk}$ can be dynamically determined by WSTAs. However, determining the impact of various values of $\Delta t_{i,g+1}^{risk}$ on the video quality performance of the WSTA as well as on its transfer is not considered in this paper and forms an important area of our future research.[9]

Summarizing, the optimal real-time cross-layer strategy s_i^{opt} consists of the PHY modulation mode selection γ_i^{opt} computed in (10), the optimal maximum number of MAC transmissions $n_{i,g,h,k}^{\max,opt}$ computed in (11), the risk-aware APP packet scheduling outlined in Table II and the APP packet prioritization described in Section III-A.

C. Anticipated Cross-Layer Strategy

In the previous subsection, we have discussed how the optimal real-time cross-layer strategy s_i^{opt} is selected in real-time. To play the resource allocation game, the WSTAs need to determine what the anticipated benefit is in terms of utility that they can derive during the current SI. For that, they cannot determine the optimal real-time cross-layer strategy because this depends on the instantaneous private information and the actual successful transmission of packets, which are not known prior to the transmission time. Instead, they will determine what is the anticipated optimal cross-layer strategy $\overline{s}_i^{opt}$. To compute the anticipated optimal cross-layer strategy, the WSTA i first estimates the anticipated private information $\overline{\mathbf{x}}_i$ based on information available for previous SIs and available channel and source models. Hence, for the anticipated cross-layer strategy, the optimal PHY mode is determined as in (10) by replacing SNR_i with $\overline{SNR}_i$. The delay-based or risk-aware packet scheduling policy can also be performed, with the only difference that now the current transmission time $Time_{i,g,h,k}^{tr}$ is replaced by the expected transmission time $\overline{Time}_{i,g,h,k}^{tr}$.

If we assume that the k_0th packet in class h_0 of GOP g is situated at the beginning of the transmission queue, then the expected transmission time for the kth packet in class h $(h \geq h_0)$ is computed as

$$\overline{Time}_{i,g,h,k}^{tr} = \sum_{l=k_0}^{K_{i,g,h_0}} \Delta t_{i,g,h_0,l}^{packet} + \sum_{m=h_0+1}^{h-1} \sum_{l=1}^{K_{i,g,m}} \Delta t_{i,g,m,l}^{packet} + \sum_{l=1}^{k-1} \Delta t_{i,g,h,l}^{packet}. \quad (12)$$

In the above equation, the first term is the average time needed to transmit the remaining packets of class h_0, the second term is the average transmission time for the packets of class h_0+1 to $h-1$, and the third term is the average transmission time for the packets of class h prior to the k-th packet. The prioritization in the APP layer is also based on the priority class illustrated in Section III-A. In the anticipated cross-layer strategy, we do not need to explicitly determine the maximum number of retransmission for each packet. Instead, we only have to calculate the expected number of packets successfully transmitted, given a certain TXOP t_i in the current SI, as

$$N_i^p = \lfloor R_i^p t_i \rfloor . \quad (13)$$

Hence, the maximum number of priority classes, H_i^{tr}, in which all packets have been transmitted in the current SI can be determined as

$$H_i^{tr} = \max \left\{ H | \sum_{h=1}^{H} \eta_{i,g,h} \leq N_i^p, 0 \leq H \leq H_i \right\}. \quad (14)$$

[9]The packet scheduling is performed when the transmission opportunities are assigned to WSTA i.

The number of packets transmitted in classes $h = 1, \cdots, H_i^{tr}$ is $\eta_{i,g,h}$. After transmitting the packets in class h $(1 \leq h \leq H_i^{tr})$, the remaining transmission opportunities are assigned to class $H_i^{tr}+1$ if $H_i^{tr} < H_i$. Hence, the number of packets transmitted in the class $H_i^{tr}+1$ is $(N_i^p - \sum_{h=1}^{H_i^{tr}} \eta_{i,g,h})$. Thus, the anticipated received video quality during one SI becomes

$$\overline{Q}_{i,g}^{rec}(t_i) = \sum_{h=1}^{H_i^{tr}} \eta_{i,g,h}\lambda_{i,h} + \left(N_i^p - \sum_{h=1}^{H_i^{tr}} \eta_{i,g,h}\right) \lambda_{i,\left(H_i^{tr}+1\right)}. \tag{15}$$

Note that we enforce $\lambda_{i,H_i^{tr}+1} = 0$ if $H_i^{tr} = H_i$. In this equation, the first term corresponds to the quality gain obtained from the video classes in which all packets have been transmitted. The last term is the quality gain from the last class (i.e the video class $H_i^{tr}+1$) from which $(N_i^p - \sum_{h=1}^{H_i^{tr}} \eta_{i,g,h})$ packets have been transmitted.

Summarizing, the anticipated optimal cross-layer strategy $\overline{s}_i^{opt}$ determines the optimal PHY modulation mode selection as in (10) using $\overline{SNR}_i$, computes the expected number of successfully transmitted packets as in (13) and adopts the delay-based or risk-aware packet scheduling policy as discussed in Section III-B. Based on $\overline{s}_i^{opt}$, the anticipated received video quality is derived as in (15).

D. Determining the True and Announced Type

To play the resource allocation game, the WSTAs not only have to proactively determine the anticipated optimal cross-layer strategy, but also they need to specify the WSTAs' willingness-to-pay $\boldsymbol{w}_i$ for a certain video quality level, i.e., accepting to pay higher/lower transfer. In other words, the willingness-to-pay $\boldsymbol{w}_i$ can be adapted based on the importance of the video sequence. Specifically, we denote the willingness-to-pay as $\boldsymbol{w}_i = [w_{i,1}, \ldots, w_{i,H_i}] \in \mathbb{R}_+^{H_i}$, where $w_{i,h}$ $(1 \leq h \leq H_i)$ represents the importance of the packets in the priority class h (hence the utility of the packet in the class h becomes $w_{i,h}\lambda_{i,h}$). For example, $w_{i,h} < 1$ means that the packets in class h are less important for WSTA i and this WSTA is less willing to pay for resources in order to transmit them (i.e., wants to pay for them only at a "discounted" cost). On the other hand, $w_{i,h} > 1$ means that the packets in class h are more important to WSTA i and this WSTA is willing to pay more for resources to ensure that they are transmitted. Based on the distortion contribution of the packets in different classes $(\lambda_{i,1} > \lambda_{i,2} > \ldots > \lambda_{i,H_i})$, we can assume that $w_{i,1} \geq \ldots \geq w_{i,H_i}$. Then, based on (15), the resulting utility $u_i(t_i, \theta_i)$ given t_i becomes

$$u_i(t_i,\theta_i) = \sum_{h=1}^{H_i^{tr}} \eta_{i,g,h} w_{i,h}\lambda_{i,h} + \left(N_i^p - \sum_{h=1}^{H_i^{tr}} \eta_{i,g,h}\right) w_{i,\left(H_i^{tr}+1\right)}\lambda_{i,\left(H_i^{tr}+1\right)}. \tag{16}$$

Note that the utility function $u_i(t_i, \theta_i)$ depends on the GOP index g. However, to simplify the notation, we ignore the subscript g in the utility function $u_i(t_i, \theta_i)$. Since the packets with different priorities have already been ordered in descending order of their quality contribution, given the allocated time t_i, only the first N_i^p packets are successfully transmitted. As shown in Section IV-A, the social decision will depend on the form of the utility function (e.g., whether the utility function is concave). Thus, to simplify the computation of the social decision, we allow the expected number of packets[10] to be a positive real number, i.e., $N_i^p = R_i^p t_i$ instead of (13). Hence, the utility function $u_i(t_i, \theta_i)$ in (16) can be rewritten as

$$u_i(t_i,\theta_i) = \sum_{h=1}^{H_i^{tr}} \frac{\eta_{i,g,h}}{R_i^p}\left(R_i^p w_{i,h}\lambda_{i,h}\right) + \left(t_i - \sum_{h=1}^{H_i^{tr}} \frac{\eta_{i,g,h}}{R_i^p}\right)\left(R_i^p w_{i,\left(H_i^{tr}+1\right)}\lambda_{i,\left(H_i^{tr}+1\right)}\right). \tag{17}$$

For each class h, we define the utility gain per unit time $\rho_{i,h}$ as $\rho_{i,h} = R_i^p w_{i,h}\lambda_{i,h}$ and transmission duration $\beta_{i,h}$ as[11] $\beta_{i,h} = \eta_{i,g,h}/R_i^p$. Then, the anticipated received video quality in (17) becomes

$$u_i(t_i,\theta_i) = \sum_{h=1}^{H_i^{tr}} \beta_{i,h}\rho_{i,h} + \left(t_i - \sum_{h=1}^{H_i^{tr}} \beta_{i,h}\right)\rho_{i,H_i^{tr}}. \tag{18}$$

From the computation of utility in (18), it is sufficient for WSTA i to report to the CSM the following parameters: the utility gain per unit time for all the classes $\rho_{i,h}$ $(1 \leq h \leq H_i)$ and transmission duration for all the classes $\beta_{i,h}$ $(1 \leq h \leq H_i)$, since they characterize the utility function over various possible resource allocations. Recall that, given a certain time allocation t_i, the type of WSTA i, θ_i, should fully determine the gained utility. Hence, the type of WSTA i, θ_i, includes

- transmission duration for each class: $\beta_{i,h}$ $(1 \leq h \leq H_i)$;
- utility gain per unit time for each class: $\rho_{i,h}$ $(1 \leq h \leq H_i)$.

To play the resource allocation game, each WSTA i adopts its revealing strategy μ_i to announce its type to CSM. The revealing strategy μ_i can be used to exaggerate, understate or truly report the values of the transmission duration $\beta_{i,h}$ and utility gain per unit time $\rho_{i,h}$. The announced values are denoted as $\hat{\beta}_{i,h} \in \mathbb{R}_+$ and $\hat{\rho}_{i,h} \in \mathbb{R}_+$, respectively. Correspondingly, the announced type $\hat{\theta}_i = \mu_i(\theta_i)$ becomes

- transmission duration for each class: $\hat{\beta}_{i,h}$ $(1 \leq h \leq H_i)$;
- utility gain per unit time for each class: $\hat{\rho}_{i,h}$ $(1 \leq h \leq H_i)$.

In this paper, we simply assume that $\hat{\rho}_{i,1} \geq \ldots \geq \hat{\rho}_{i,h}$ such that the utility function derived at CSM side still has the concavity property. Hence, the announced utility function which CSM believes is computed as

$$u_i(t_i,\hat{\theta}_i) = \sum_{h=1}^{H_i^{tr}} \hat{\beta}_{i,h}\hat{\rho}_{i,h} + \left(t_i - \sum_{h=1}^{H_i^{tr}} \hat{\beta}_{i,h}\right)\hat{\rho}_{i,H_i^{tr}}. \tag{19}$$

Note that $\hat{\rho}_{i,H_i^{tr}+1} = 0$ if $H_i^{tr} = H_i$.

[10]To simplify the notation, we use N_i^p for both the discrete and the continuous version of expected number of successfully transmitted packet. The same holds true for the utility $u_i(t_i, \theta_i)$.

[11]Note that we ignore the subscript g here.

IV. Mechanism Design for Resource Allocation

A. VCG Mechanism Design

As mentioned in the introduction, the key challenges for efficient multiuser wireless resource management are two-fold. First, an efficient and fair mechanism for allocating the TXOPs among WSTAs needs to be developed. Second, since the efficiency of the resource management algorithms heavily depend on the truthful declaration of the resource requirements by the selfish WSTAs, a mechanism needs to be implemented in the CSM to prevent the WSTAs from exaggerating their resource requirement and misusing the available resources. To address the above two challenges, in the proposed resource allocation, the VCG mechanism renders two tasks: 1) it makes a "social decision" which results in a fair allocation of resources among WSTAs, i.e., it determines $\mathbf{T}(\hat{\theta}, \boldsymbol{\mathcal{R}})$; 2) it computes the transfers $\tau(\hat{\theta}, \boldsymbol{\mathcal{R}})$ for the WSTAs according to the amount of resources it has allocated to them. We define the aggregated system utility [14] as

$$u^{sys}\left(\mathbf{T}(\hat{\theta}, \boldsymbol{\mathcal{R}}), \hat{\theta}\right) = \sum_{i=1}^{M} u_i(t_i, \hat{\theta}_i). \tag{20}$$

In the deployed VCG mechanism, the social decision allocates the resource $\boldsymbol{\mathcal{R}}$ 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:

$$\mathbf{T}^{opt}(\hat{\theta}, \boldsymbol{\mathcal{R}}) = \arg\max_{\mathbf{T}(\hat{\theta}, \boldsymbol{\mathcal{R}})} u^{sys}\left(\mathbf{T}(\hat{\theta}, \boldsymbol{\mathcal{R}}), \hat{\theta}\right)$$
$$s.t. \sum_{i=1}^{M} t_i \le t_{SI},\ t_i \ge 0,\ \text{for } 1 \le i \le M. \tag{21}$$

Then, based on the optimal resource allocation $\mathbf{T}^{opt}(\hat{\theta}, \boldsymbol{\mathcal{R}})$, i.e., $[t_1^{opt}, \ldots, t_M^{opt}]$, the CSM computes the transfers for all WSTAs according to the inconvenience they cause to the competing WSTAs. The inconvenience a WSTA i causes to another WSTA j is quantified in terms of the utility drop incurred by the WSTA j due to the resources that are allocated to WSTA i. We define $\hat{\theta}_{-i}$ as the type profile of all WSTAs except i, i.e., $\hat{\theta}_{-i} = (\hat{\theta}_1, \ldots, \hat{\theta}_{i-1}, \hat{\theta}_{i+1}, \ldots, \hat{\theta}_M)$ and $\mathbf{T}_{-i}(\hat{\theta}_{-i}, \boldsymbol{\mathcal{R}})$ as the resource allocation when WSTA i is not participating in the resource allocation game, i.e., $\mathbf{T}_{-i}(\hat{\theta}_{-i}, \boldsymbol{\mathcal{R}}) = [t_1, \ldots, t_{i-1}, t_{i+1}, \ldots, t_M]$. Then, the transfer for WSTA i can be computed as

$$\tau_i(\hat{\theta}, \boldsymbol{\mathcal{R}}) = \sum_{k \ne i} u_k\left(t_k^{opt}, \hat{\theta}_k\right) - \max_{\mathbf{T}_{-i}(\hat{\theta}_{-i}, \boldsymbol{\mathcal{R}})} \sum_{k \ne i} u_k(t_k, \hat{\theta}_k). \tag{22}$$

The first term of (22) 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.

B. Solutions for the Social Decision in the VCG Mechanism

To solve the optimization problem in (21) and (22), we first prove that both the announced utility function $u_i(t_i, \hat{\theta}_i)$ and the aggregated system utility are concave.

Lemma 1: The announced utility function $u_i(t_i, \hat{\theta}_i)$ is concave with respect to the allocated resources t_i.

Proof: From (19), we note that, given the announced type $\hat{\theta}_i$, the utility function $u_i(t_i, \hat{\theta}_i)$ is piece-wise linear and monotonically increasing. Since we assumed that $\hat{\rho}_{i,1} \ge \ldots \ge \hat{\rho}_{i,h}$, we can conclude that the utility function is concave with respect to t_i [23].

Proposition 1: The aggregated utility function $(u^{sys}(\mathbf{T}(\hat{\theta}, \boldsymbol{\mathcal{R}}), \hat{\theta}))$ is concave with respect to the allocated resource $\mathbf{T}(\hat{\theta}, \boldsymbol{\mathcal{R}})$.

Proof: Using Lemma 1, which proves that $u_i(t_i, \hat{\theta}_i)$ is concave in t_i, we can conclude that $u^{sys}(\mathbf{T}(\hat{\theta}, \boldsymbol{\mathcal{R}}), \hat{\theta})$ is concave because the sum of M concave functions is concave [23].

From Section III-D, we know that the announced type for each WSTA i includes the transmission duration for each class $\hat{\beta}_{i,h}$ and the utility gain per unit time for each class $\hat{\rho}_{i,h}$. To compute the system utility obtained using the optimal resource allocation $\mathbf{T}^{opt}(\hat{\theta}, \boldsymbol{\mathcal{R}})$, we first re-order the utility gain per unit time for each class $\hat{\rho}_{i,h}$ in the descending order for all the WSTAs. One example for two WSTAs could be $\hat{\rho}_{2,1} \ge \hat{\rho}_{1,1} \ge \hat{\rho}_{2,2} \ge \ldots \ge \hat{\rho}_{1,H_1}$. If $\hat{\rho}_{i,h} = \hat{\rho}_{i',h'}$, one of the classes is randomly chosen first. For explanation simplicity, we re-denote the m-th utility gain per unit time after re-ordering as φ_m ($1 \le m \le C_{tot}$, where $C_{tot} = \sum_{i=1}^{M} H_i$) and the corresponding transmission duration for that class available for transmission as π_m. In other words, if the utility gain per unit time φ_m corresponds to $\hat{\rho}_{i,h}$, then $\pi_m = \hat{\beta}_{i,h}$. We now get $\varphi_1 \ge \ldots \ge \varphi_{C_{tot}}$. The optimal resource allocation can be found by greedily assigning the resources to the classes with a higher utility gain per unit time. Formally, we assign the resource π_1 to the first class with the utility gain per unit time φ_1, π_2 to the second class with the utility gain per unit time φ_2, until the total resource t_{SI} is consumed. The algorithm is illustrated in Table III. Let C_{tr} be the maximum number of classes to which transmission opportunities are allocated, i.e.

$$C_{tr} = \max\left\{ m \,\middle|\, \sum_{l=1}^{m} \pi_l \le t_{SI} \right\}. \tag{23}$$

Similar to (19), the optimal aggregated utility is obtained by

$$u^{sys}\left(\mathbf{T}^{opt}(\hat{\theta}, \boldsymbol{\mathcal{R}}), \hat{\theta}\right) = \sum_{m=1}^{C_{tr}} \varphi_m \pi_m + \left(t_{SI} - \sum_{m=1}^{C_{tr}} \pi_m\right) \varphi_{C_{tr}+1}. \tag{24}$$

Note that we enforce that $\varphi_{C_{tr}+1} = 0$ if $C_{tr} + 1 > C_{tot}$. The resource allocated to WSTA i is accordingly computed as

$$t_i^{opt} = \sum_{\substack{m \le C_{tr} \\ m \in \boldsymbol{\mathcal{M}}(i)}} \pi_m + \left(t_{SI} - \sum_{m=1}^{C_{tr}} \pi_m\right) I\left(C_{tr} + 1 \in \boldsymbol{\mathcal{M}}(i)\right) \tag{25}$$

where $\boldsymbol{\mathcal{M}}(i)$ is the index set of the utility gain per unit time from WSTA i, and $I(C_{tr}+1 \in \boldsymbol{\mathcal{M}}(i))$ is the indicator function which equals 1 if $C_{tr} + 1 \in \boldsymbol{\mathcal{M}}(i)$, and 0 otherwise.

TABLE III
ALGORITHM FOR FINDING OPTIMAL RESOURCE ALLOCATION AND CORRESPONDING AGGREGATED UTILITY

Initialization: $m \Leftarrow 1$, $t_{left} \Leftarrow t_{SI}$, $u^{sys} \Leftarrow 0$, $t_i^{opt} \Leftarrow 0$ for $1 \le i \le M$.
Repeat:
 Find i such that $m \in \mathcal{M}(i)$;
 $t_i^{opt} \Leftarrow t_i^{opt} + \min\{t_{left}, \pi_m\}$;
 $u^{sys} \Leftarrow u^{sys} + \varphi_m \min\{t_{left}, \pi_m\}$;
 $t_{left} \Leftarrow t_{left} - \min\{t_{left}, \pi_m\}$;
 $m \Leftarrow m + 1$.
Until: $t_{left} \le 0$ or $m > C_{tot}$.
Output: u^{sys} and t_i^{opt} for $1 \le i \le M$.

The transfer computation can be solved using the same algorithm illustrated in Table III.

C. 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 [18].

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 [18].

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 multiuser wireless video transmission case.

Proposition 2: 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

$$\begin{aligned} \upsilon_i(\hat{\theta}, \theta_i, \boldsymbol{\mathcal{R}}) &= u_i\left(t_i^{opt}, \theta_i\right) + \tau_i \\ &= u_i\left(t_i^{opt}, \theta_i\right) + \sum_{k \ne i} u_k\left(t_k^{opt}, \hat{\theta}_k\right) \\ &\quad - \max_{\mathbf{T}_{-i}(\hat{\theta}_{-i}, \boldsymbol{\mathcal{R}})} \sum_{k \ne i} u_k(t_k, \hat{\theta}_k) \\ &= \left[u_i\left(t_i^{opt}, \theta_i\right) + \sum_{k \ne i} u_k\left(t_k^{opt}, \hat{\theta}_k\right)\right] \\ &\quad - \max_{\mathbf{T}_{-i}(\hat{\theta}_{-i}, \boldsymbol{\mathcal{R}})} \sum_{k \ne i} u_k(t_k, \hat{\theta}_k). \end{aligned} \tag{26}$$

Note that, we expand the transfer τ_i in the first line with the computation in (22) 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

$$\begin{aligned} \kappa_i^{opt} &= \left(\overline{s}_i^{opt}, \mu_i^{opt}\right) = \arg \max_{\kappa_i = (\overline{s}_i, \mu_i) \in \boldsymbol{\mathcal{S}}_i \times \boldsymbol{\mathcal{V}}_i} \upsilon_i(\hat{\theta}, \theta_i, \boldsymbol{\mathcal{R}}) \\ &= \arg \max_{\kappa_i = (\overline{s}_i, \mu_i) \in \boldsymbol{\mathcal{S}}_i \times \boldsymbol{\mathcal{V}}_i} \\ &\quad \left\{ \left[u_i\left(t_i^{opt}, \theta_i\right) + \sum_{k \ne i} u_k\left(t_k^{opt}, \hat{\theta}_k\right)\right] \right. \\ &\quad \left. - \max_{\mathbf{T}_{-i}(\hat{\theta}_{-i}, \boldsymbol{\mathcal{R}})} \sum_{k \ne i} u_k(t_k, \hat{\theta}_k) \right\} \\ &= \arg \max_{\kappa_i = (\overline{s}_i, \mu_i) \in \boldsymbol{\mathcal{S}}_i \times \boldsymbol{\mathcal{V}}_i} \\ &\quad \left\{ \left[u_i\left(t_i^{opt}, \theta_i\right) + \sum_{k \ne i} u_k\left(t_k^{opt}, \hat{\theta}_k\right)\right] \right\} \\ &\quad - \max_{\mathbf{T}_{-i}(\hat{\theta}_{-i}, \boldsymbol{\mathcal{R}})} \sum_{k \ne i} u_k(t_k, \hat{\theta}_k). \end{aligned} \tag{27}$$

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

$$\arg \max_{\kappa_i = (\overline{s}_i, \mu_i) \in \boldsymbol{\mathcal{S}}_i \times \boldsymbol{\mathcal{V}}_i} \left\{ \left[u_i\left(t_i^{opt}, \theta_i\right) + \sum_{k \ne i} u_k\left(t_k^{opt}, \hat{\theta}_k\right)\right] \right\}. \tag{28}$$

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:

$$\max_{\mathbf{T}(\hat{\theta}, \boldsymbol{\mathcal{R}})} \left[u_i(t_i, \theta_i) + \sum_{k \ne i} u_k(t_k, \hat{\theta}_k)\right] \tag{29}$$

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.

D. VCG Mechanism Design for Cross-Layer Optimization

In the above subsection, 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. In this subsection, we summarize the steps involved

TABLE IV
TRANSMITTED VIDEO SEQUENCES FOR FIVE WSTAs

WSTA	Video sequences (CIF@30Hz, 64 fames)	Desired rate (kbps)	$\lambda_{i,h}\,(1 \leq h \leq H_i)$
1	*Foreman*	512	0.1538, 0.1246, 0.0656, 0.0152, 0.0087
2	*Foreman*	512	0.1538, 0.1246, 0.0656, 0.0152, 0.0087
3	*Coastguard*	1024	0.1451, 0.1138, 0.0534, 0.011, 0.0087
4	*Coastguard*	1024	0.1451, 0.1138, 0.0534, 0.011, 0.0087
5	*Mobile*	2048	0.1383, 0.0942, 0.0405, 0.0097, 0.0067

in the implementation of VCG mechanism in the wireless network.

The implementation of the VCG mechanism for our resource allocation is depicted in Fig. 1. At the beginning of each SI, WSTA $i\,(1 \leq i \leq M)$ first estimates their own anticipated private information $\overline{\mathbf{x}}_i = (\overline{SNR}_i, \overline{\xi}_i)$. Next, it selects the optimal joint strategy κ_i^{opt} to maximize its own payoff v_i, based on (27), 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 (21) and computes the transfer as in (22) 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 $\mathbf{x}_i$ to transmit the video data.

E. Complexity Analysis for Mechanism Design

At the CSM side, the social decision and transfer computation is done for each SI. We use the "flop" (floating-point operation) as a measure of complexity, which will provide us an estimation of the computation complexity required for performing the social decision and transfer computation. Also, based on this we can determine how the time grows with the increasing number of WSTAs [23]. For the social decision and transfer computation, we need to sort the utility gain per unit time from all WSTAs. The number of "flops" required by this "sorting" is approximately $(\sum_{i=1}^{M} H_i)^2$. By using the algorithm proposed in Table III, the number of "flops" in computing the optimal aggregated utility and resource allocations is approximately $3(\sum_{i=1}^{M} H_i)$. The transfer computation for each WSTA i has the same complexity as that for computing the optimal aggregated utility and resource allocations. Therefore, the total number of "flops" incured by the CSM is $(\sum_{i=1}^{M} H_i)^2 + 3(\sum_{i=1}^{M} H_i) + M(3(\sum_{i=1}^{M} H_i)) \approx O(\sum_{i=1}^{M} H_i)^2$.

V. SIMULATION RESULTS

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

In Section IV, we determined that if the CSM deploys the VCG mechanism to allocate resources among WSTAs, then the competing WSTAs have no incentives to lie about their own type. 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. We assume that the network consists of five autonomous WSTAs transmitting real-time video sequences. We validate the efficiency of the proposed solution using our wireless streaming test-bed [30].

To enable efficient video streaming over wireless networks, each WSTA needs to be able to cope with instantaneous bandwidth variations due to time-varying channel conditions and network congestion (many competing WSTAs), etc. To adapt to the time-varying available resources, a flexible encoding algorithm is needed that provides graceful degradation and adaptability to a wide range of wireless channel conditions. Hence, although the concepts proposed in this paper can potentially be deployed with state-of-the-art nonscalable coding with bitstream switching, this usually entails higher complexity and smaller granularity for real-time bandwidth adaptation and packet prioritization. Consequently, we use scalable video coding schemes based on Motion Compensated Temporal Filtering (MCTF) using wavelets [21]. Such 3-D wavelet video compression is attractive for wireless streaming applications since it provides on-the-fly adaptation to channel conditions, support for a variety of wireless receivers with different resource capabilities and power constraints, and easy prioritization of various coding layers and video packets.

The parameters of the deployed video sequences are summarized in Table IV. The video applications are considered to tolerate a delay[12] of 533 ms [29]. To compete for the wireless resources, we assume that all five WSTAs deploy optimal cross-layer strategies as discussed in Section III-B. The delay-based greedy scheduling policy is adopted. The willingness-to-pay attitude is not considered in this experiment, i.e., $w_{ih} = 1\ (1 \leq i \leq M, 1 \leq h \leq H_i)$. The channel conditions experienced by the five WSTAs are assumed to be similar, having an average SNR of 23 dB and a variation across the various SIs of around 5 dB. We also assume $t_{SI} = 106$ ms, which amounts to approximately one fifth of the duration of one GOP.

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 is lying about its type and 2) WSTA 5 is lying about its type, but other WSTAs are telling the truth. Table V shows the percentage of time allocated to the various WSTAs and the transfers and corresponding PSNRs for the two cases. To improve the readability of the results, the difference of PSNR and transfers between the two scenarios is also computed.[13]

[12]During the simulations, for simplicity, we assume that the packets within one GOP have the same delay deadline.

[13]Negative transfer means WSTAs pay the transfer to CSM. In the VCG mechanism, the transfer is always negative.

TABLE V
TIME ALLOCATION, TRANSFERS AND CORRESPONDING PSNRS FOR THE VARIOUS WSTAS IN TWO CASES—A) NO WSTA IS LYING ABOUT ITS TYPE AND B) ONLY ONE WSTA IS EXAGGERATING ITS TYPE

WSTA	No WSTAs lying			WSTA 5 lying but other WSTAs not lying			Δ PSNR (dB)	Δ Transfer
	Percentage of time (%)	PSNR (dB)	Transfers[14]	Percentage of time (%)	PSNR (dB)	Transfer		
1	13.60	34.7430	-27.1581	9.51	33.4424	-24.1772	***-1.30***	***2.98***
2	13.62	34.7430	-27.2074	9.68	33.4078	-24.5336	***-1.34***	***2.67***
3	18.66	30.6180	-35.5029	14.99	29.6479	-33.3464	***-0.97***	***2.16***
4	18.73	30.6007	-35.6499	14.61	29.8008	-32.6240	***-0.80***	***3.03***
5	35.40	30.3217	-50.4189	51.22	32.1102	-89.3044	***1.79***	***-38.89***

TABLE VI
TIME ALLOCATION, TRANSFERS, AND CORRESPONDING PSNRS FOR THE VARIOUS WSTAS IN THE CASE WHEN ONE WSTA DEPLOYS A LESS SMART STRATEGY—A FIXED PHY MODE

WSTA	Optimal cross-layer strategy			Only WSTA2 deploying fixed modulation			Δ PSNR (dB)	Δ Transfer
	Percentage of time (%)	PSNR (dB)	Transfers	Percentage of time (%)	PSNR (dB)	Transfer		
1	20.00	31.1246	-34.5552	22.33	31.3083	-36.5306	0.18	-1.98
2	20.00	31.0719	-34.5552	12.32	26.3952	-10.2705	***-4.68***	***24.28***
3	20.00	31.1048	-34.5552	21.84	31.2636	-35.9439	0.16	-1.39
4	20.00	30.9942	-34.5552	21.84	31.3662	-35.9439	0.37	-1.39
5	20.00	31.0510	-34.5552	21.67	31.2817	-35.7994	0.23	-1.24

TABLE VII
TIME ALLOCATION, TRANSFERS, AND CORRESPONDING PSNRS FOR THE VARIOUS WSTAS IN THE CASE WHEN ONE WSTA DEPLOYS A LESS SMART STRATEGY—A FIXED MAC STRATEGY

WSTA	Optimal cross-layer strategy			Only WSTA2 deploying fixed retransmission			Δ PSNR (dB)	Δ Transfer
	Percentage of time (%)	PSNR (dB)	Transfers	Percentage of time (%)	PSNR (dB)	Transfer		
1	20.00	31.1246	-34.5552	20.00	31.1246	-34.3276	0.00	0.23
2	20.00	31.0719	-34.5552	20.00	29.6328	-34.3276	***-1.44***	***0.23***
3	20.00	31.1048	-34.5552	20.00	31.0916	-34.3276	-0.01	0.23
4	20.00	30.9942	-34.5552	20.00	31.1044	-34.3276	0.11	0.23
5	20.00	31.0510	-34.5552	20.00	31.0713	-34.1000	0.02	0.46

When WSTAs adopt the best cross-layer strategies and reveal the true types, the resources are allocated by maximizing the system-wide utilities, i.e., the resources are efficiently allocated among WSTAs. However, when WSTA 5 exaggerates its own type, the video quality (PSNR) for this station is improved by 1.78 dB, 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 0.8–1.3 dB. The transfers incurred by these WSTAs is only very little decreased.

From these experiments, it becomes clear that indeed, by using the VCG mechanism, the lying of WSTAs is penalized through a significantly increased transfer. From this experiment, we can also conclude that conventional resource allocation schemes, e.g., air-fair allocation [2], [24], which heavily depend on the truthfulness of WSTAs, will result in significantly worse performance when WSTAs exaggerate their requirements, as they do not have a mechanism to penalize WSTAs for misusing resources.

B. Impact of Adopting Smart Cross-Layer Strategies

In this experiment, we assess the impact which the cross-layer strategy optimization at one WSTA has on its own video quality performance as well as on the competing WSTAs. We term the ability of WSTAs to efficiently deploy and adapt their cross-layer strategies based on channel conditions and source characteristics as the "smartness" with which WSTAs play the resource management game. To assess the importance of smartly adopting cross-layer strategies for efficiently playing the resource management game, we assume that all five WSTAs transmit the same video sequence: *Coastguard* (CIF@30 Hz) at 512 kbps. The channel conditions are kept the same as in the previous experiment. This simulation does not yet include the risk-aware scheduling and willingness-to-pay attitude.

Table VI and VII depict the experienced PSNRs, allocated time as well as transfers of all WSTAs. In the first scenario, all WSTAs deploy optimal cross-layer strategies. In the second scenario, WSTA 2 deploys a less smart (sub-optimal) cross-layer strategy as compared to other WSTAs—it adopts a fixed modulation mode. In the third scenario, WSTA 2 deploys another less smart cross-layer strategy—this time it uses a fixed retransmission limit per packet.

The results clearly show that by deploying a less smart strategy, the performance of WSTA 2 is degraded with respect to that of the other WSTAs. Specifically, WSTA 2 experiences a PSNR loss of around 4.5 dB when the fixed PHY mode is used

TABLE VIII
TIME ALLOCATION, TRANSFERS, AND CORRESPONDING PSNRS FOR THE VARIOUS WSTAS IN THE CASE WHEN ONE WSTA HAS HIGHER WILLINGNESS-TO-PAY

WSTA	All WSTAs have the same willingness-to-pay attitude			WSTA 2 has higher willingness-to-pay			Δ PSNR (dB)	Δ Transfer
	Percentage of time (%)	PSNR (dB)	Transfers	Percentage of time (%)	PSNR (dB)	Transfer		
1	13.60	34.7430	-27.1581	10.96	33.7528	-24.9685	-0.99	2.19
2	13.62	34.7430	-27.2074	19.28	35.7834	-50.9421	***1.04***	***-23.73***
3	18.66	30.6180	-35.5029	16.92	30.2402	-34.3023	-0.38	1.20
4	18.73	30.6007	-35.6499	17.27	30.2688	-34.2686	-0.33	1.38
5	35.40	30.3217	-50.4189	35.57	30.3085	-50.5941	-0.01	-0.18

TABLE IX
TIME ALLOCATION, TRANSFERS, AND CORRESPONDING PSNRS FOR THE VARIOUS WSTAS IN THE CASE WHEN ONE WSTA HAS LESS WILLINGNESS-TO-PAY

WSTA	All WSTAs have the same willingness-to-pay attitude			WSTA 5 has less willingness-to-pay			Δ PSNR (dB)	Δ Transfer
	Percentage of time (%)	PSNR (dB)	Transfers	Percentage of time (%)	PSNR (dB)	Transfer		
1	13.60	34.7430	-27.1581	14.22	35.0154	-25.5593	0.72	1.60
2	13.62	34.7430	-27.2074	14.06	35.0366	-25.2261	0.29	1.98
3	18.66	30.6180	-35.5029	21.35	31.2965	-33.2650	0.68	2.24
4	18.73	30.6007	-35.6499	22.50	31.5362	-34.9607	0.94	0.69
5	35.40	30.3217	-50.4189	27.87	28.8121	-23.5513	***-1.51***	***26.87***

and around 1.5 dB loss when the MAC retransmission is fixed with respect to the initial scenario, where all WSTAs deploy smart cross-layer strategies for transmission. Interestingly, deploying a fixed PHY mode also leads to a lower transfer. However, this transfer decrease also leads to an unacceptable PSNR drop. The reason for this transfer decrease is that by fixing its PHY mode, WSTA 2 derives a lower type than other WSTAs given the same amount of resources. Hence, the CSM allocates this WSTA a lower amount of transmission time, but also a lower transfer. In the third scenario, by deploying a fixed MAC retransmission scheme, WSTA 2 incurs a 1.5 dB PSNR loss and it is charged a similar transfer compared to scenario 1.

Summarizing, the results of these experiments highlight that the WSTAs obtain the best payoff by deploying an optimal cross-layer strategy. Also, fortunately, when a WSTA deploys a less smart cross-layer strategy, this does not have a significant impact on the other WSTAs' PSNR performance.

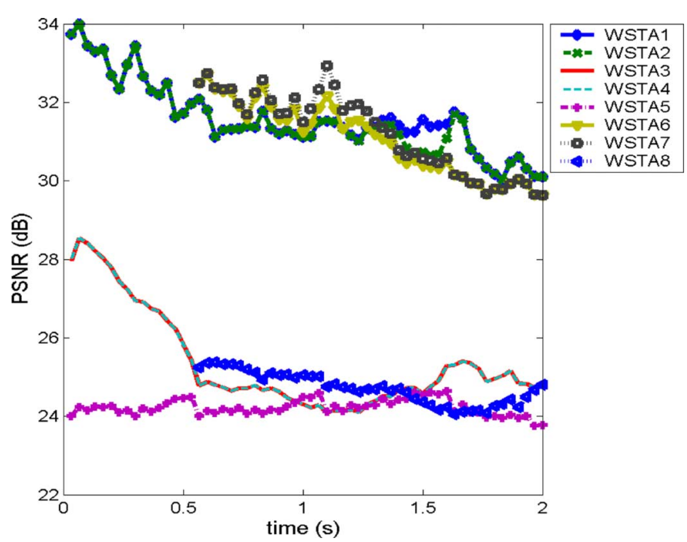

Fig. 2. PSNRs of 8 WSTAs in the case where WSTAs 6∼8 join into the network at time 0.5 s.

C. *Willingness-to-Pay Attitude*

In this simulation, we compare the performance of WSTAs having different willingness-to-pay attitudes. For the experiments, we keep the same settings as in Section V-A. Three different scenarios are considered to investigate the impact of the willingness-to-pay attitude of WSTAs: 1) all WSTAs have the same willingness-to-pay (i.e., $w_{ih} = 1, 1 \leq i \leq M$, $1 \leq h \leq H_i$); 2) the other WSTAs are kept the same, but WSTA 2 has a higher willingness-to-pay, i.e., $w_{2h} = 5, 1 \leq h \leq H_2$; and 3) the other WSTAs are kept the same, but WSTA 5 is less willing to pay for resources, i.e., $w_{ih} = 0.5, 1 \leq h \leq H_5$. However, we note that the problem of accurately determining the willingness-to-pay for each WSTA is very challenging, as this depends on many factors, such as the network congestion, video content, how long the user desires to stay in the network, how much tokens (money) the user possess, etc. (see [31] for more details). In scenario 1, the performance of the WSTAs is the same as in Section V-A. However, in scenario 2, WSTA 2 has an important video sequence to transmit and hence, it increases its willingness-to-pay for resources. Table VIII shows the performance of all WSTAs in scenario 1 and 2. From the table, we note that WSTA 2 has an increased PSNR by 1 dB, but also that this WSTA is now paying an increased transfer. Due to the higher willingness-to-pay of WSTA 2, the PSNRs of other WSTAs have been decreased (a drop in PSNR in the range of 0.3–0.9 dB was measured), while the transfers for these WSTAs are decreased. Table IX shows the performance of all WSTAs in scenario 1 and 3. Due to its reduced willingness-to-pay, WSTA 5 experiences a 1.5 dB PSNR drop, but also its transfer is reduced by 26.87. Note that the reduced willingness-to-pay of WSTA 5 positively affects the performance of other WSTAs, i.e., their PSNRs are increased and their payment to the CSM is decreased. This is because the reduced willingness-to-pay of WSTAs reduces the "value" of the resources and hence, the other WSTAs can obtain resources at a lower cost.

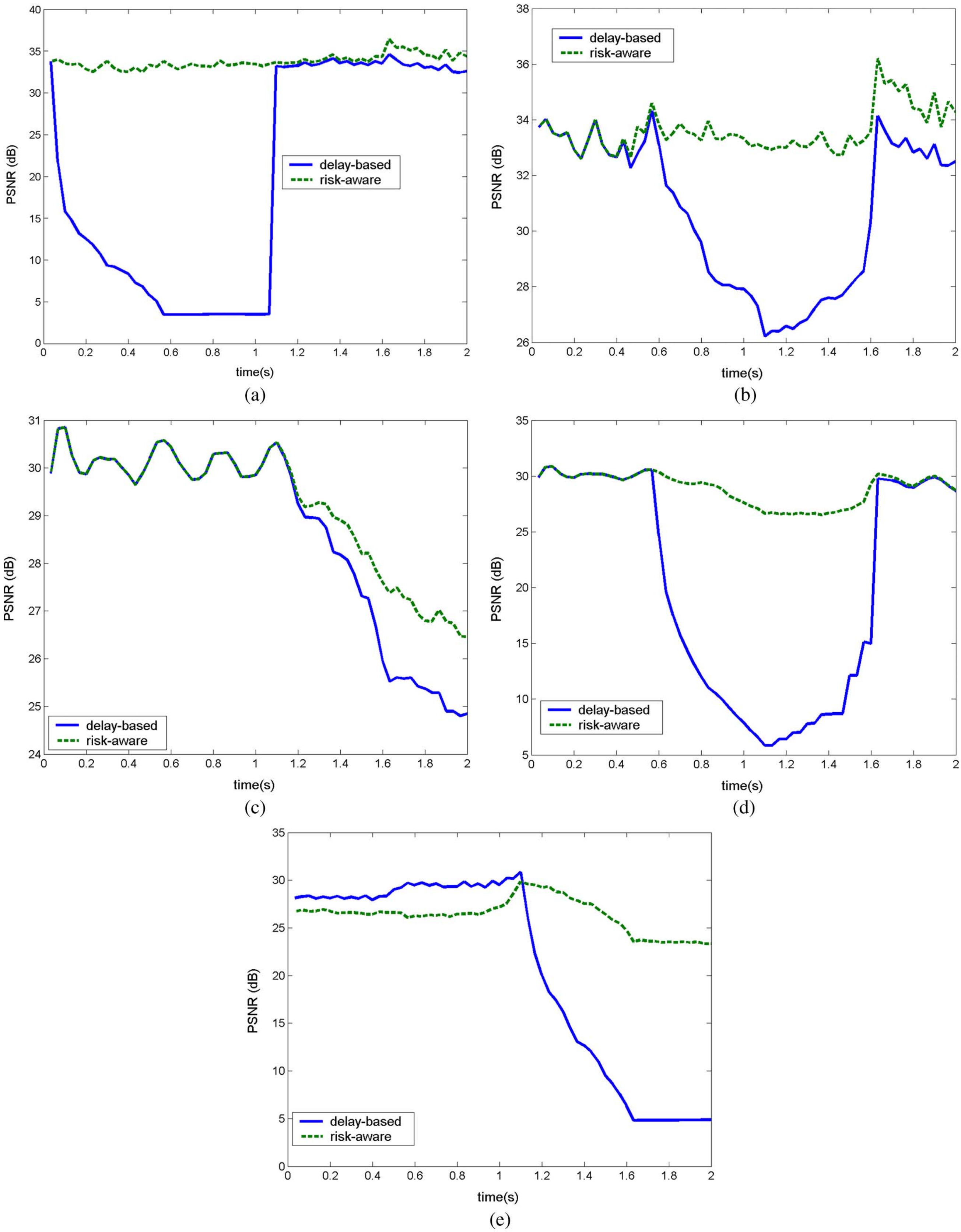

Fig. 3. PSNRs of the five WSTAs using delay-based packet scheduling and risk-aware packet scheduling (a) WSTA 1, (b) WSTA 2, (c) WSTA 3, (d) WSTA 4, and (e) WSTA 5.

D. 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 1. After 0.5 s, 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. Fig. 2 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.

E. Risk-Aware Packet Scheduling

Next, we investigated the effect of risk-aware scheduling on the resource allocation game. Note, however, that a full investigation of various types of risk and algorithms for adapting the risk over time based on channel conditions, network congestion, video characteristics, etc., forms a topic of our future research. We consider a similar simulation setup as in Section V-A, but this time WSTAs 1∼5 experience poor channel conditions during the time intervals 0.5∼1 s, 1∼1.5 s, 1.5∼2 s, 1∼1.5 s and 1.5∼2 s, respectively. We consider two simulation scenarios: 1) all the WSTAs deploy a delay-based scheduling policy; 2) all the WSTAs deploy a risk-aware scheduling policy. Fig. 3(a)–(e) depict the PSNR variation of the reconstructed video of all the five WSTAs in the first 2 s. We notice that, when the WSTAs experience a poor channel condition, the delay-based packet scheduling algorithm significantly degraded the received video qualities of all the WSTAs in terms of PSNR—WSTAs 1, 4, and 5 experience frame freezes, thereby resulting in an unacceptable user experience. However, by deploying the risk-aware packet scheduling, the received video qualities of all the WSTAs are improved significantly, and the video is gracefully degraded. The risk-aware packet scheduling algorithm improves the experienced video quality because, when the channel conditions are poor, the risk-aware scheme is guaranteeing that the higher priority packets in each GOP are received. This guarantees that the quality is gracefully degraded when the network is temporarily very congested or the WSTA experiences a bad channel conditions (low SNR).

VI. Conclusions

In this paper, we model the wireless resource allocation problem as a “game” played among competing WSTAs wanting to stream real-time video. For this, we adopt the VCG mechanism to ensure that resources are allocated fairly (according to a predetermined “social decision”) 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, which represent their strategy 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. Moreover, our results show that deploying “smart” cross-layer strategies for playing the resource management game does indeed lead to a significantly improved video quality performance. Furthermore, by deploying the proposed risk-aware scheduling WSTAs can dynamically avoid requesting resources when the network is congested, thereby reducing their transfers without significantly impacting the resulting video quality. By increasing their willingness-to-pay for resources, WSTAs can influence the resource management game by ensuring that resources are allocated to them independent on their actual derived utility. Summarizing, our results show that the presented game-theoretic solution for wireless resource management emulates a “market”-driven approach, where users that are richer or smarter can derive a better performance over time.

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