GAME-THEORETIC PARADIGM FOR RESOURCE MANAGEMENT IN SPECTRUM AGILE WIRELESS NETWORKS

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ABSTRACT

We propose a new way of architecting the wireless multimedia communications systems by jointly optimizing the protocol stack at each station and the resource exchanges among stations. We model wireless stations as rational players competing for available wireless resources in a dynamic repeated game. We investigate and quantify the system performance and the impact of different cross-layer strategies deployed by wireless stations onto their own performance as well as the competing station performance. We show through simulations that the proposed game-theoretic resource management outperforms alternative techniques such as air-fair time and equal time resource allocation in terms of the total system utility.

1. INTRODUCTION

Recently, significant contributions have been made to enhance the performance of wireless multimedia using cross-layer optimization (see [1] for a review of the topic). However, the optimization has been performed 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 wireless communication systems by enabling wireless stations (WSTAs) to dynamically compete for wireless resources by proactively adapting their optimized cross-layer (Application-MAC-PHY) transmission strategies. Current solutions for wireless resource allocation (e.g. equal time and air-fair time [3]) do not scale with the number of WSTAs, e.g. WLAN 802.11e [2], or do not consider the utility impact such as video quality and delay constraints. Importantly, existing solutions do not prevent WSTAs from exaggerating their resource needs at the expense of competing WSTAs. Game-theoretic based resource allocation can potentially eliminate these limitations.

Game theory has been used in prior research to resolve resource allocation issues for wireless networks in a distributed and scalable manner [4]. For instance, in [4], a new solution to the problem of engineering non-monetary incentives for edge-based wireless access services was proposed which offers both higher throughput for bursty data and more stable allocation for real-time applications. However, previous research has not considered the benefits of dynamic resource exchanges among stations as opposed to (global) resource allocation for various applications. Wireless multimedia applications can especially benefit from dynamic resource, information and constraints sharing among stations due to their delay sensitivity, loss tolerance, and time-varying bandwidth requirements.

We propose a new game-theoretic paradigm that allows WSTAs to dynamically compete for wireless resources by (continuously) adapting their cross-layer optimized transmission strategies, thereby requiring different amounts of wireless resources and deriving different corresponding benefits (utilities) in terms of multimedia quality. We consider an Opportunistic Spectrum Agile Radio (OSAR) network infrastructure [5][6][7] in which stations can opportunistically utilize multiple wireless channels, thereby dynamically gathering additional resources to satisfy multimedia delay and bandwidth requirements. Our main focus is on investigating and quantifying the impact of the (number and type of) cross-layer strategies deployed by each station on its own video quality performance as well as on the other "players" (stations) when the proposed mechanism-based resource allocation is used.

The paper is organized as follows. Section 2 presents the OSAR system we consider in this paper. Section 3 introduces mechanism design deployed at CSM and the transfer computation. Section 4 gives the cross-layer strategies WSTAs adopt to "play" the resource allocation game and illustrates the impacts on its own utilities. Section 5 provides the simulation results which is followed by the conclusions in Section 6.

2. SYSTEM MODELING

We consider an OSAR network with N channels (spectrum bands). We define *primary* users as the users for which the spectrum is originally assigned. The secondary users are selfish and autonomous and try to maximize their own benefits from the network. We assume the presence of M *secondary* users (interchangeably called WSTAs in this paper), which utilize the unused portions of the spectrum in an opportunistic fashion based on spectral availability, in a manner that minimizes interference to primary users. In this paper, WSTAs can access multiple channels at the same time. In addition, we assume the performance of channel $j, 1 \le j \le N$, for WSTA $i, 1 \le i \le M$, is characterized by the experienced Signal to Noise Ratio (SNR) SNR_{ij}. To manage the available wireless network resource, i.e. transmission time over the various channels, we assume the presence of a central spectrum moderator (CSM) that manages the available channels, and dynamically allocates transmission opportunities (TXOPs) to the participating WSTAs (see Figure 1). The proposed polling-based MAC resource management scheme decides and enforces the allocation of TXOPs for each service interval (SI). The length of each SI is t_{SI}. The number of TXOPs per SI equals Q.
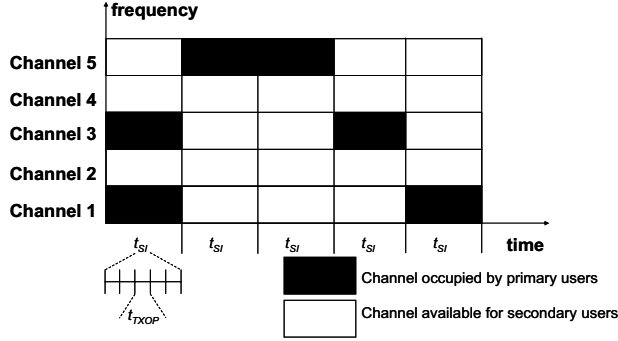
Figure1: Description of OSAR network setup

3. MECHANISM-BASED RESOURCE ALLOCATION

In this section we discuss how the CSM will interact with WSTAs in order to allocate the TXOPs. The basic tool used by the CSM is the so-called *mechanism design* [8] in which a CSM renders two major tasks: (i) it decides about the allocation of TXOPs to different users, $\mathbf{Q} = [\mathbf{q}_1,...,\mathbf{q}_M] \in \mathbb{N}^{N \times M}$ which is called the allocation matrix that represents the number of TXOPs allocated to user i on channel j in the current SI; (ii) it determines the vector of *transfers* to be charged to each user, $\boldsymbol{\tau} = [\tau_1,...,\tau_M]^T \in \Re^M$. The transfers can be of monetary nature or other computational network resources. Both $\mathbf{Q}$ and $\boldsymbol{\tau}$ are functions of the private information (or "types" in game theoretic terms), represented by $\boldsymbol{\theta}_i$ for user i, transmitted to the CSM by each WSTA. We define the collection of private information as the matrix $\boldsymbol{\theta} = [\boldsymbol{\theta}_1, ..., \boldsymbol{\theta}_M]$. The private information for WSTAs in our problem, which will be discussed in the next section, incorporates the quality of each channel, the importance of current packets for each user, users deployed cross-layer strategies, etc. Based on the private information and allocated time, user i can derive a *utility* function, denoted by $U_i(\mathbf{q}_i, \boldsymbol{\theta}_i)$, in terms of expected video quality, which will be described in next section. User i announces a *function* of its private information, $\hat{\boldsymbol{\theta}}_i$, with the aim of maximizing its own total payoff which is equal to the video utility minus paid transfers. We also define $\boldsymbol{\Omega}_k = \{\mathbf{P} \in \mathbb{N}^{N \times k} \mid \mathbf{P}\mathbf{e}_k = Q\mathbf{e}_k\}$ where $\mathbf{e}_k$ is a column vector of ones of size k, i.e. $\boldsymbol{\Omega}_k$ contains all feasible TXOP allocation matrices in a network of k users. The CSM computes the $\mathbf{Q}$ that maximizes the *aggregate utility*:

$$\max_{\mathbf{Q}=[\mathbf{q}_1,...\mathbf{q}_M]\in\boldsymbol{\Omega}_M} \sum_{i=1}^{M} U_i(\mathbf{q}_i, \hat{\boldsymbol{\theta}}_i) \qquad (1)$$

We call the solution to the above optimization $\mathbf{Q}^*(\hat{\boldsymbol{\theta}})$.

The goal of mechanism design, and in particular collecting transfers from WSTAs, is to induce honesty to users in announcing the true private type. This is a crucial point in wireless resource allocation as over-provisioning by users can degrade the performance of the whole network. Hence, we implement a special form of mechanism called Clarke mechanism [8]. In this kind of mechanism, the time allocations is performed according to (1) and

the transfers are computed as:

$$\tau_i(\boldsymbol{\theta}) = \sum_{k \neq i} U_k(\mathbf{Q}^*(\hat{\boldsymbol{\theta}}), \hat{\boldsymbol{\theta}}_k) -$$
$$\max_{\tilde{\mathbf{Q}}=[\tilde{\mathbf{q}}_1,...\tilde{\mathbf{q}}_{i-1},\tilde{\mathbf{q}}_{i+1},...\tilde{\mathbf{q}}_l]\in\boldsymbol{\Omega}_{l-1}} \sum_{k \neq i} U_k(\tilde{\mathbf{q}}_k, \hat{\boldsymbol{\theta}}_k) \qquad (2)$$

In words, the amount that user i pays is equal to the utility loss it causes to all other users by its presence in the network. We say user i is "smart" if, given the rules of the resource management, i.e. equations (1) and (2), it can adjust its strategies such that it maximizes its own payoff, i.e. $U_i(\mathbf{q}_i, \boldsymbol{\theta}_i) + \tau_i$.

Proposition: Given the Clarke mechanism above, all smart users will find it optimal for their own payoff to announce the true private information to the CSM, i.e., $\hat{\boldsymbol{\theta}}_i = \boldsymbol{\theta}_i$, regardless of other WSTA's strategies.

The proof can be found in [8]. This way, by levying transfers according to Clarke transfers above, one can make sure that no WSTA will have incentives to lie about its private type for the hope of earning a higher payoff.

4. USERS' STRATEGIES AND EXPECTED UTILITY

Based on the mechanism introduced in the above section, each WSTA announces its private information according to the cross-layer strategies it adopts, the experienced channel conditions and the video characteristics. Let $\mathbf{a}_i = [\text{PHY}_i^l \quad \text{MAC}_i^m \quad \text{APP}_i^n] \in \mathcal{A}_i^{tot}$ be a vector of cross-layer adaptation strategies that can be deployed by WSTA i, where $\mathcal{A}_i^{tot} = \mathcal{A}_i^{PHY} \times \mathcal{A}_i^{MAC} \times \mathcal{A}_i^{APP}$ denotes the joint set of all possible strategies at the PHY, MAC and APP layers of WSTA i, respectively. In general, the size of the cross-layer strategies set is very large. In this paper, we limit the cross-layer strategies deployed at the stations to include only application-layer R-D scheduling, MAC layer retransmission and PHY layer modulation and coding schemes.

Each WSTA i is *playing* the resource allocation game by adjusting its cross-layer transmission strategies. The utility per packet is denoted as Δ_v and represents the distortion reduction the receiver gains by correctly decoding the video data of the packet v.

In the following, we briefly discuss these strategies and illustrate how they affect the utility the WSTAs can obtain by engaging in the wireless resource management game.

Let us consider WSTA i with a vector of scheduled packets $[v_i^1,...,v_i^K]$ to be transmitted over current SI. The deployed PHY strategy $\text{PHY}_i^l \in \mathcal{A}_i^{PHY}$ together with SNR_{ij} determines the bit-error rate $P_e(\text{PHY}_i^l, SNR_{ij})$ of WSTA i over channel j, the corresponding packet loss rate $P_{ij}^{L_i}(v_i^k)$ for packet $v_i^k, 1 \leq k \leq K$ with average packet size L_i. The optimal modulation and coding for channe j is by maximizing the effective rate $R_{ij}^{phy} \cdot (1 - P_{ij}^{L_i}(v_i^k))$ where R_{ij}^{phy} is the physical layer throughput computed as in [9]. Hence the PHY strategy PHY_i^l summarizes the selected modulation and coding schemes

for all the channels.

Given the modulation and coding schemes, the maximum number of transmissions for packet v_k^i can be dynamically computed as:

$$T_{ij}^{\max}(v_i^k) = \frac{R_{ij}^{phy} \cdot (t^{delay}(v_i^k) - t_{ij}^{current})}{L_i} \qquad (3)$$

where $t^{delay}(v_i^k) = \min\{$delay constraint for the packet v_k^i, the end of current SI$\}$ and $t_{ij}^{current}$ is the time user i starts transmitting packet v_i^k over channel j assuming the whole SI is allocated to user i. The probability of successfully receiving packet v_i^k can be calculated as $P_{ij}^{succ}(v_i^k) = 1 - (P_{ij}^L(v_i^k))^{T_{ij}^{\max}(v_i^k)}$. The average number of retransmissions until the packet is successfully received or the retransmission limit is reached, can be computed as $T_{ij}^{mean}(v_i^k) = P_{ij}^{succ} / (1 - P_{ij}^L(v_i^k))$. Hence the MAC strategy MAC_{ij}^m summarizes the maximum number of transmissions for all channels.

Assuming the allocated time to user i is $\mathbf{q}_i = [q_{i1}, ..., q_{iN}]^T, 0 \le q_{ij} \le Q$, then the average number of packets, Nop_{ij}^{ave}, that can be transmitted correctly on channel j in current SI is:

$$Nop_{ij}^{ave}(q_{ij}) = \max\{Nop \mid \sum_{k=k_0}^{k_0+Nop-1} \frac{L_i}{R_{ij}^{phy}} T_{ij}^{mean}(v_i^k) \le q_{ij} \frac{t_{SI}}{Q}\} \quad (4)$$

where k_0 is the index of the first packet to be transmitted over channel j. Hence, the expected utility that WSTA i can obtain, given the allocated TXOP vector $\mathbf{q}_i$, is the sum utilities of the successfully transmitted packets over all the channels, which is given by

$$U_i(\mathbf{q}_i, \mathbf{\theta_i}) = \sum_{k=1}^{Nop_i^{tot}} \Delta_{v_i^k} \qquad (5)$$

where $Nop_i^{tot}(\mathbf{q}_i) = \sum_{j=1}^{N} Nop_{ij}^{ave}(q_{ij})$.

From the above expected utility, we define the vector of private information, $\mathbf{\theta_i}$, announced to the CSM as $\mathbf{\theta}_i = [\mathbf{Nop}_i, \mathbf{\Delta}_i]$ where $\mathbf{Nop}_i = [Nop_{i1}^{ave}(Q)...Nop_{iN}^{ave}(Q)]$, $\mathbf{\Delta}_i = [\Delta_{v_i^1}...\Delta_{v_i^k}]$. Upon receiving the private information from the WSTAs, the CSM performs the time allocation and transfer collection as in (1) and (2) with utility function

$$U_i(\mathbf{q}_i, \hat{\mathbf{\theta}}_i) = \sum_{k=1}^{Nop_i^\theta} \Delta_{v_i^k} \text{ ,where } Nop_i^\theta = \left\lfloor \sum_{j=1}^{N} \frac{q_{ij}}{Q} N_{ij}^{ave}(Q) \right\rfloor. \text{ As a}$$

result of the deployed mechanism, users announce their true information and TXOPs are allocated such that the sum of users' utilities is maximized. The convex relaxation of the optimization programs at the CSM are in the form of convex programs that can be solved efficiently to derive Q^* and $\mathbf{\tau}$.

5. SIMULATION RESULTS

In the simulation section, we assume the network consists of five autonomous WSTAs and two available channels. WSTAs transmit their video content over the network and the reported outcome is the average experienced PSNR for each user. The selected sequences (see Table 1) are CIF at 30Hz. We use the recently-developed Motion Compensated Temporal Filtering based scalable video coding [10]. We use a Group Of Pictures (GOP) structure with 16 frames in each GOP, and temporal decomposition with 4 temporal levels. The video sequences and bandwidth requirements for all WSTAs are listed in table 1. We chose $t_{SI} = 100$ ms and $Q = 10$. The experienced SNRs on the different channels for all users vary between 18dB and 29dB.

In the first simulation, we compare the performance of mechanism-based time allocation regime with two conventional methods: the *equal-time* method in which equal number of TXOPs is allocated to all WSTAs and the *air-fair time* method in which TXOPs are allocated proportional to the announced rate requirements. Table 2 shows the experienced PSNR for each WSTA. Since the equal-time allocation is a content-unaware scheme and does not consider channel conditions, WSTAs 4 and 5, which need the most amounts of time, are allocated insufficient number of TXOPs and experience a loss of 3dB in PSNR compared to the mechanism-based method. In the air-fair time scenario, the *selfish* and autonomous WSTAs have incentives to exaggerate about their rate requirements. In our simulation, WSTAs 1 to 5 exaggerate about their requirement each by more than 50%. Hence, WSTAs 4 and 5 are still allocated insufficient number of TXOPs and, thus, experience losses of 3dB and 0.8 dB in PSNR respectively compared to our proposed method. Furthermore, the mechanism-based time allocation scheme takes into account video characteristics and channel conditions, and, therefore, dynamically divides the network resource among WSTAs according to their requirements. Figure 2 shows the PSNRs experienced by WSTA 1 in air-fair scenario and mechanism-based scenario. This fact is highlighted in Figure 2 where user 1, due to its dynamic video characteristics, requires between frames 175 and 200 more bandwidth. This is not met by the air-fair method but is fulfilled by our mechanism that allocates this dynamically.

Further, we show the spectrum agility property of our proposed method by assuming that channel 2 is suddenly occupied by a primary user at the time 5s. Figure 3 and Figure 4 show the experienced PSNRs and TXOP allocations to the WSTAs. They show that the transition from two channels to one channel is smooth and the PSNR of all users remains above 27dB even though the network becomes more congested.

6. CONCLUSIONS

We consider the wireless resource allocation for multimedia transmission over OSAR infrastructure. The proposed mechanism-based method dynamically divides the wireless resource by taking into account various video characteristics, time-varying channel conditions and available cross-layer transmission strategies within WSTAs. We introduce and show through simulations, that the mechanism-based method outperforms the conventional methods such as air-fair time and equal time in terms of PSNR. Besides, the spectrum agility of our method, which is predicted by theory, is confirmed through simulation results.

Table1: Video and the corresponding bitrate for WSTAs

WSTA	1	2	3	4	5
Video	foreman	foreman	coastguard	mobile	mobile
Bitrate (Kbps)	512	512	1024	1536	2048

Table2: PSNRs (dB) of WSTAs

WSTA	1	2	3	4	5
Airfair	34.28	34.94	34.23	29.94	32.82
Equaltime	34.90	34.94	34.26	29.94	30.00
Mechanism	34.85	34.78	34.16	32.96	33.67
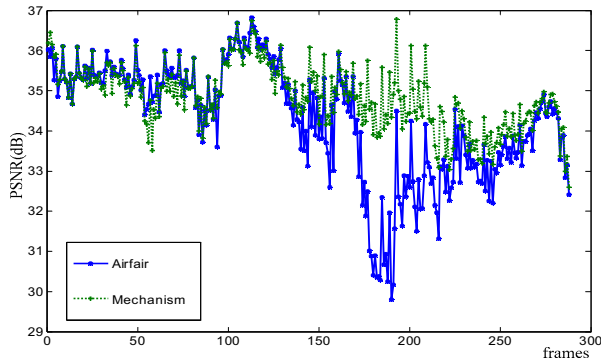
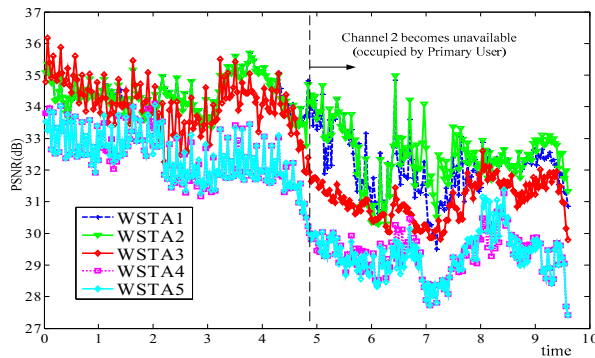Figure 2: experienced PSNR of WSTA 1 in air-fair time and mechanism-based methods

Figure 3: Experienced PSNRs of 5 WSTAs when channel 2 is
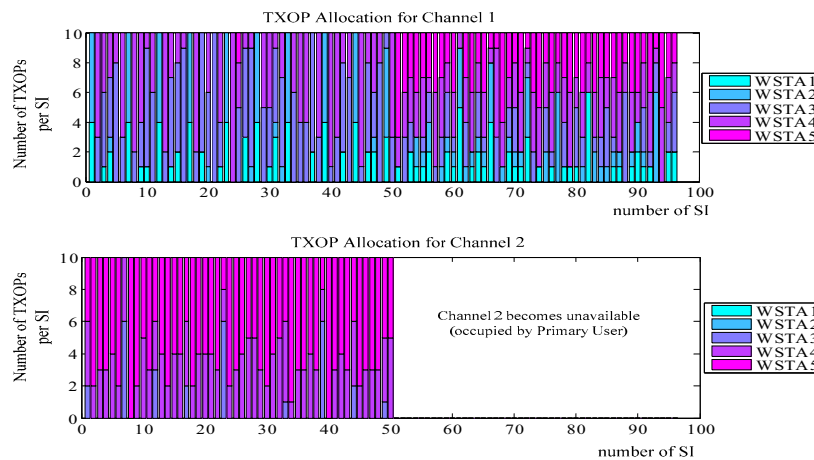
occupied by a primary user

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Figure 4: TXOP allocations to WSTAs when channel 2 is occupied by a primary user