# Coalition-Based Resource Negotiation for Multimedia Applications in Informationally Decentralized Networks

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***Abstract*—Designing efficient and fair solutions for dividing the network resources in a distributed manner among self-interested multimedia users is recently becoming an important research topic because heterogeneous and high bandwidth multimedia applications (users), having different quality-of-service requirements, are sharing the same network. Suitable resource negotiation solutions need to explicitly consider the amount of information exchanged among the users and the computational complexity incurred by the users. In this paper, we propose decentralized solutions for resource negotiation, where multiple autonomous users self-organize into a coalition which shares the same network resources and negotiate the division of these resources by exchanging information about their requirements. We then discuss various resource sharing strategies that the users can deploy based on their exchanged information. Several of these strategies are designed to explicitly consider the utility (i.e., video quality) impact of multimedia applications. In order to quantify the utility benefit derived by exchanging different information, we define a new metric, which we refer to as the value of information. We quantify through simulations the improvements that can be achieved when various information is exchanged between users, and discuss the required complexity at the user side involved in implementing the various resource negotiation strategies.**

***Index Terms*—Axiomatic bargaining solutions, coalition game, marginal contribution, multiuser multimedia resource management, network resource management, Shapley value, value of information.**

## I. Introduction

EMERGING multimedia applications such as multimedia streaming services, multipoint video conferencing, multiuser gaming, and peer-to-peer multimedia streaming are transmitted over congested wired or wireless networks. These networks can be shared by multiple applications (users) that have different quality-of-service (QoS) requirements. Hence, developing efficient and fair resource negotiation strategies for multimedia users is a challenging task. While various resource negotiation strategies can be developed based on the users' requirements, implementing these strategies requires the users to exchange information and perform complex computations. Therefore, it is essential to quantify the benefit that users can derive by deploying different resource negotiation strategies.

Various resource negotiation strategies for multiuser environments have been proposed for wired networks (e.g., asynchronous transfer mode (ATM) networks [1]) and wireless networks (e.g., [2], [3]), including recently cognitive radio networks (e.g., [4]–[6]). Some strategies have been designed for centralized networks, where a central resource coordinator optimizes the network resource allocation or distributes the resources based on its predetermined fairness rules. For example, in [4], the resources are allocated to users such that the total rates (sum of rates) are maximized. In addition, several fairness policies such as max-min fairness or proportional fairness are proposed as resource negotiation.

Alternatively, decentralized approaches for the resource negotiation strategies are also proposed, which provide improved scalability as the number of users in the network increases. For instance, a decentralized flow control algorithm that can enable users to achieve a max-min fair resource allocation in ATM networks is proposed in [1]. In [5], a decentralized spectrum sharing policy for a contention free channel assignment is proposed based on a predetermined fairness rule. In [6], an algorithm for self-organizing users is proposed to group the users and locally share the available spectrum. While these strategies enable the users to share the available network resources based on decentralized approaches, they are developed based on predetermined fairness rules and predetermined information exchanges. Hence, these approaches cannot be adapted for multimedia users, who have different information availability and requirements.

In this paper, we propose decentralized solutions for resource negotiation strategies, where multiple users self-organize into coalitions which share the same network resources and can negotiate the resource division based on information exchanged about their QoS quality-of-service requirements. Several approaches to coalition formation for self-interested multiagents have been suggested in different environments [7]–[12]. For example, several strategies to form agent-organized networks (AONs) in dynamic and distributed environments, where agents in AONs determine tasks that they jointly perform, are proposed in [7] and [8]. In [9] and [10], coalition formation problems are studied when only uncertain or incomplete information is available. As in, e.g., [11], [12], our focus is on settings where the information required for coalition formation can be obtained

Manuscript received November 21, 2007; revised February 06, 2009. First published April 22, 2009; current version published May 15, 2009. This work was supported in part by NSF CAREER Award CCF-0541867 and in part by grants from ONR. The material in this paper was presented in part at the Fifteenth IEEE International Conference on Image Processing (ICIP), San Diego, CA, October 2008. The associate editor coordinating the review of this manuscript and approving it for publication was Prof. Madjid Merabti.

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Digital Object Identifier 10.1109/TMM.2009.2017638

based on information exchanges. The impact of information exchange on coalition formation is studied in [13], which shows that agents will form coalitions only if sufficient information has been exchanged among them. However, the study in [13] focuses on the effect of the frequency of predetermined information exchanges on coalition formation, and does not consider the impact of different types of information exchanges.

Unlike prior works [9], [10], which divide resources using fixed value division solutions with a predetermined set of information exchanges, we study how different information exchanges impact the coalition formation, the negotiation strategies for sharing resources, and ultimately, the resource allocations to each user. To model the resource division among the users sharing network resources, we adopt coalition game theory [14], [15], which focuses on the division of the coalition value (e.g., aggregated utility) based on fairness axioms [16]. Based on coalition game theory, we propose a decentralized algorithm that enables incoming multimedia users to negotiate resources with the already established coalitions, while explicitly considering the improvement of the coalition's value as well as individually achieved multimedia utility.

This paper is organized as follows. Section II describes the considered networks and the information about the requirements of multimedia users. In Section III, we describe how users negotiate network resource with a coalition. In Section IV, we discuss various resource negotiation strategies that can be deployed by the users given different information exchanges. The system dynamics and the corresponding convergence are analyzed in Section V. The value of information is defined and the performance of different strategies is compared in Section VI. Simulation results are presented in Section VII and the conclusions are drawn in Section VIII.

## II. Decentralized Network Resource Negotiation

### A. Decentralized Network Resource Negotiation

To illustrate our proposed framework, we model network resources as being divided into multiple frequency bands (channels[1]) that are accessible to users, as in cognitive radio networks [4]–[6]. We also assume that the network resources (i.e., channels) can be divided using time division multiple access (TDMA).[2] Users sharing the same channel negotiate their *transmission opportunities* (TXOPs), which represent a *fraction* of the service interval ($t_{SI}$), based on their deployed channel sharing strategy. Hence, given the information $\hat{\mathbf{I}}$ exchanged for the channel sharing strategy, and the available channels $\boldsymbol{\theta}$, the network resource solution determines both *what* channels and *how many* TXOPs are allocated to the $M$ users, i.e.,

$$[(j_1, \tau_{j_1 1}), \ldots, (j_M, \tau_{j_M M})]$$

where $\tau_{j_k k}$ denotes the TXOP allocated to user $k$ in channel $j_k \in \boldsymbol{\theta}$. Note that the proposed solution for the resource negotiation depends on the *information exchanged* by the users. In the considered system set-up, multimedia users can proactively select and join a channel, and then share the channel with the already existing users using multiple channel access methods such as TDMA. In this paper, we use coalition game theory solutions to enable the users to select coalitions (channels, etc.), negotiate and fairly distribute resources with the users in the coalition.

Note that the proposed framework for the resource negotiation can be used without modifying the current communications protocols, since the negotiation is implemented at the application layer. Since different information exchanges can induce distinct channel sharing strategies between the participating users, we first discuss the information that can be exchanged among the multimedia users.

### B. Information Exchanges

There are $N$ channels, denoted as $\boldsymbol{\theta} = \{1, \ldots, N\}$, which are available for users to transmit their multimedia data. A user $k$ can access the channels $\boldsymbol{\theta}_k \subseteq \boldsymbol{\theta}$ in its proximity. The experienced channel condition[3] for a user, i.e., the signal-to-noise ratio (SNR), is used to determine its maximum rates that can be achieved in the channels. We denote the maximum rate that user $k$ can achieve using channel $j \in \boldsymbol{\theta}_k$ as $R_{jk}^M$. Hence, the set of maximum achievable rates for user $k$ in channels $\boldsymbol{\theta}_k$ is expressed as $\mathbf{R}_k^M(\boldsymbol{\theta}_k) = \{R_{jk}^M | j \in \boldsymbol{\theta}_k\}$. Moreover, the user specific information, which captures the characteristics of multimedia traffic, can also be used. This information can be conveyed using well-known traffic specification (TSPEC) techniques. We denote the set of available TSPECs for user $k$ as $\Psi_k$, where a TSPEC $\psi_k \in \Psi_k$ can include the peak data rate, the mean data rate, the maximum burst size, and the maximum permissible delay [17]. These parameters can be used to compute the effective rate $g_k(\psi_k)$ specified in a deployed TSPEC $\psi_k$, where user $k$ can select among $H_k$ TSPECs, i.e., $|\Psi_k| = H_k$ [18]. Note that we deploy multiple TSPECs [18] in order to allow the users to adjust their resource requirements in a scalable manner, thereby providing graceful adaptation as the number of users in the coalition increases. In addition, the achievable utility $U_k(g_k(\psi_k))$ for the effective rate $g_k(\psi_k)$, and the minimum required utility $U_k^m$ can be additionally included in the information about TSPECs. Hence, the information about TSPEC for user $k$ is expressed as $\mathbf{I}_{TS_k} = \{\psi_k, U_k(g_k(\psi_k)), U_k^m\}$ for $\psi_k \in \Psi_k$.

Channel sharing strategies can explicitly consider the utility impact based on $U_k(g_k(\psi_k))$ and $U_k^m$ in the information about TSPEC for user $k$. A widely-used quality measure, peak signal-to-noise ratio (PSNR), is used to represent the utility for the multimedia users in this paper. Therefore, the information about user $k$ can be expressed as

$$\mathbf{I}_k = \left\{\boldsymbol{\theta}_k, \mathbf{R}_k^M(\boldsymbol{\theta}_k), \mathbf{I}_{TS_k}\right\}. \tag{1}$$

Finally, the set of complete information about all the users in the entire network is called a global information, denoted by $\mathbf{I}_G = \{\mathbf{I}_k | k \in \boldsymbol{\theta}\}$ with $\mathbf{I}_{TS_k} = \{\psi_k, U_k(g_k(\psi_k)), U_k^m\}$ for $\psi_k \in \Psi_k$. The global information $\mathbf{I}_G$ will be used to obtain a theoretical bound for the value of information exchanges in Section VI.

[1] In this paper, the terms *channel* and *(network) resource* are interchangeably used.

[2] While we illustrate the proposed framework for TDMA, it could also be deployed for frequency division multiple access (FDMA) or even both of TDMA and FDMA like in cognitive radio networks.

[3] Since the allocated TXOPs are non-overlapping, interferences induced by multiple channel access can be ignored.

**Procedure 1** Resource Negotiation Process of User $k$

**Given:** available channel $\boldsymbol{\theta}_k$, set of acceptable strategies $\boldsymbol{\mathcal{G}}^*_{\boldsymbol{\theta}_k}$.

1: Selecting Coalition; $j^* = \arg\max_{j \in \boldsymbol{\theta}_k} \left[\mathcal{G}^*_j(v(C_j \cup \{k\}))\right]_k$.
2: Joining Coalition; $C_{j^*} \leftarrow C_{j^*} \cup \{k\}$.
3: Determining Channel Sharing Strategy; $\mathcal{G}^*_{j^*}$.
4: Dividing Coalition Value;
$\mathcal{G}^*_{j^*}(v(C_{j^*})) = \left[\left[\mathcal{G}^*_{j^*}(v(C_{j^*})\right]_1, \ldots, \left[\mathcal{G}^*_{j^*}(v(C_{j^*})\right]_{m_{j^*}}\right]$.
5: Determining TSPEC $\psi^*_l$;
$\psi^*_l \in \Psi_l$: $U_l(g_l(\psi^*_l)) = [\mathcal{G}^*_{j^*}(v(C_{j^*}))]_l, \forall\, l \in C_{j^*}$.
6: Determining TXOP $\tau_{j^*l}$; $g_l(\psi^*_l) = \tau_{j^*l} \cdot R^M_{j^*l}, \forall\, l \in C_{j^*}$.

### C. Utility-Based Network Resource Negotiation

In this section, we consider the involved steps for the decentralized resource negotiation. Among the available channel sharing strategies $\boldsymbol{\mathcal{G}}$, users first negotiate and determine a channel sharing strategy $\mathcal{G} \in \boldsymbol{\mathcal{G}}$, which will be used for the TXOP allocation among the users. To explicitly consider the utility impact of the allocated TXOPs on multimedia users, we will discuss several utility-based channel sharing strategies. The utility-based channel sharing strategy $\mathcal{G}$ is defined as follows.

*Definition 1 (Utility-Based Channel Sharing Strategy):* A *utility-based channel sharing strategy* in coalition $C_j$ with $m_j$ users is a function $\mathcal{G}: \mathbb{R}_+ \rightarrow \mathbb{R}^{m_j}_+$, defined as

$$\mathcal{G}(v(C_j)) = \left([\mathcal{G}(v(C_j))]_1, \ldots, [\mathcal{G}(v(C_j))]_{m_j}\right) \quad (2)$$

where $v(C_j)$ denotes the coalition value that represents the total utility achieved by the $m_j$ users in $C_j$, i.e., $v(C_j) = \sum_{l=1}^{m_j} U_l(g_l(\psi_l))$. $[\mathcal{G}(v(C_j))]_k$ denotes the negotiated coalition value to user $k$ and $\mathbb{R}_+$ denotes the space of nonnegative real numbers.

As shown in the above definition, the TXOPs in channel $j$ are divided based on the utility impact since $[\mathcal{G}(v(C_j))]_k$ can be converted to the corresponding TXOPs $\tau_{jk}$. The resource negotiation process for user $k$ is depicted in Fig. 1, and the corresponding steps are presented in Procedure 1.

User $k$ negotiates the channel sharing strategies $\boldsymbol{\mathcal{G}}$ with coalitions in its available channels $\boldsymbol{\theta}_k$. We will discuss several utility-based channel sharing strategies and investigate their properties in Section IV. The negotiation outcomes are the set of acceptable strategies $\boldsymbol{\mathcal{G}}^*_{\boldsymbol{\theta}_k} = \{\mathcal{G}^*_j | j \in \boldsymbol{\theta}_k\}$, which will be discussed in Section III. An additional step that allows users to improve their utilities by switching coalitions can be included in Procedure 1. Specifically, user $k$ which is currently in coalition $C_j$ will switch to another coalition $C_{j'}$ if $U_k(g_k(\psi_k)) - U_k(g_k(\psi'_k)) > U^{th}_k$, where $U^{th}_k$ denotes a predetermined threshold, which can be determined by taking into account the overhead incurred by user $k$ when it switches coalitions.

## III. Decentralized Negotiation on Channel Sharing Strategies

In this section, we describe how users can negotiate the channel sharing strategies with a coalition. When a user tries to join a coalition, *both* the user and the coalition need to agree on a resource sharing strategy that will be used for the TXOP allocations in that channel. As discussed, several channel sharing strategies, denoted by $\boldsymbol{\mathcal{G}}$, can be selected and implemented for dividing TXOPs. We assume that the available channel sharing strategies $\boldsymbol{\mathcal{G}}$ are known to the users. Different information exchanges and computational complexity are required to implement distinct channel sharing strategies.

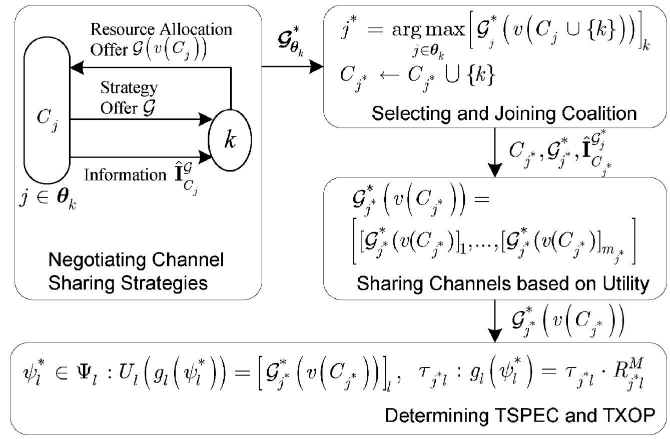


Fig. 1. Network resource negotiation process.

The coalition and the incoming user sequentially exchange information in order to negotiate the channel sharing strategies. The coalition will accept the resource allocation offers of the user only if these offers do not decrease its coalition value. The user will accept the channel sharing strategies offered by the coalition only if the strategies do not decrease its utility. In the subsequent section, we model the negotiation on the channel sharing strategies as an extensive game of *alternating offers* [14] between a user and a coalition.

### A. Modeling Negotiation on Channel Sharing Strategies as an Extensive Game

The negotiation on channel sharing strategies can be modeled as a game between a user and a coalition. One of the users in the coalition is selected as a *leader*, who will play the game of negotiating the channel sharing strategies with the incoming user on behalf of the users in the coalition. Specifically, the negotiation is modeled as an extensive game $\langle \mathcal{N}, \mathcal{H}, P, (\succsim_k) \rangle$ as in [14], where

- $\mathcal{N}$ is set of users; $\mathcal{N} = \{L_j, k\}$, where the leader $L_j$ of $C_j$ and incoming user $k$;
- $\mathcal{H}$ consists of the history of the offers (i.e., strategy or resource allocation) and the actions (i.e., accept or reject); $(a_l)_{l=1,\ldots,L} \in \mathcal{H}$, where $a_l = \begin{cases} (ACK_{L_j}, \mathcal{G}_r), & \text{if } L_j \text{ offers} \\ (ACK_k, \mathcal{G}_r(v(C_j))), & \text{otherwise;} \end{cases}$
- $P$ is the user function that denotes the player who takes an action; $P(a_l) = \begin{cases} L_j, & \text{if } l \text{ is odd} \\ k, & \text{otherwise;} \end{cases}$
- $\succsim_k$ is the preference relation of user $k \in \mathcal{N}$ on the coalition value; both a user and a coalition prefer higher coalition values.[4]

This extensive game can be analyzed by considering sequential offers from the users and their corresponding actions. In the

[4]For a single user $k$, its utility can be considered as the coalition value of user $k$ only, i.e., $v(\{k\})$.

next section, we propose an algorithm that implements the extensive game of alternating offers for the resource negotiation strategies considered in our paper.

### B. Decentralized Negotiation of Channel Sharing Strategies Based on Alternating Offers

An algorithm for negotiating channel sharing strategies between a coalition $C_j$ with $m_j$ users and an incoming user $k$ is presented in Algorithm 2. The detailed steps involved in the negotiation are described next.

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**Algorithm 2** Negotiation on Channel Sharing Strategies between User $k$ and Coalition $C_j$

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**Given:** available set of strategies $\boldsymbol{\mathcal{G}}$, coalition value $v(C_j)$, negotiation time limit $T_k^A$, patience factor $\delta_k^{t(r)}$.

1: $r \leftarrow 1$, $t(r) \leftarrow 0$, $ACK_{L_j} \leftarrow \emptyset$, $MSG_{L_j} = \{\mathcal{G}, \mathbf{I}_{C_j}^{\mathcal{G}}\} \leftarrow \{\emptyset, \emptyset\}$, $ACK_k \leftarrow R$, $MSG_k = \{\mathcal{G}, \mathcal{G}(v(C_j \cup \{k\}))\} \leftarrow \{\emptyset, \emptyset\}$, $\boldsymbol{\mathcal{G}}_j^* \leftarrow \emptyset$, $v(\{k\}) \leftarrow 0$.
2: **while** $ACK_k \neq T$ **do**
3:   **if** $ACK_k = A$ **then**
4:     **if** $\sum_l [\mathcal{G}(v(C_j \cup \{k\}))]_l \geq v(C_j)$ **then**
5:       $ACK_{L_j} \leftarrow A$, $MSG_{L_j} \leftarrow \{\mathcal{G}_r \in \boldsymbol{\mathcal{G}}, \mathbf{I}_{C_j}^{\mathcal{G}_r}\}$
6:     **else**
7:       $ACK_{L_j} \leftarrow R$, $MSG_{L_j} \leftarrow \{\mathcal{G}_r \in \boldsymbol{\mathcal{G}}, \mathbf{I}_{C_j}^{\mathcal{G}_r}\}$
8:   **else**
9:     $ACK_{L_j} \leftarrow R$, $MSG_{L_j} \leftarrow \{\mathcal{G}_r \in \boldsymbol{\mathcal{G}}, \mathbf{I}_{C_j}^{\mathcal{G}_r}\}$
10:   **if** $ACK_{L_j} = A$ **then**
11:     $\mathcal{G}_j^* \leftarrow \mathcal{G}_{r-1}$
12:   **if** $t(r) \geq T_k^A$ or $\delta_k^{t(r)} = 0$ **then**
13:     $ACK_k = T$
14:   **else**
15:     **if** $[\mathcal{G}_r(v(C_j \cup \{k\}))]_k \geq U_k^m$ and $\delta_k^{t(r)} \cdot [\mathcal{G}_r(v(C_j))]_k \geq v(\{k\})$ **then**
16:       $ACK_k \leftarrow A$, $MSG_k \leftarrow \{\mathcal{G}_r, \mathcal{G}_r(v(C_j \cup \{k\}))\}$, $v(\{k\}) \leftarrow [\mathcal{G}_r(v(C_j))]_k$
17:     **else**
18:       $ACK_k \leftarrow R$
19:   $r \leftarrow r + 1$

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*1) Initialization (Line 1):* Negotiation on channel sharing strategies begins with the request from an incoming user $k$ to join a coalition. If the coalition joining request signal is received, one of the users in the coalition is selected as a leader. Note that the initial coalition values (i.e., at time $t = 0$) are $v(C_j)$ for coalition $C_j$ and $v(\{k\}) = 0$ for the incoming user $k$. The following steps discuss the interactions between the leader and the user at negotiation round $r$ after $(r-1)$ negotiations.

*2) Negotiation of Channel Sharing Strategies (Line 2–19):*

•*Leader's Decision on Resource Allocation Offers and its Alternative Strategy Offers (In Line 3–9):* If $ACK_k = T$, then the leader terminates the negotiation with user $k$ since user $k$ cannot continue the negotiation. If $ACK_k = R$, the leader simply offers the next available strategy $\mathcal{G}_r$ and the information $\mathbf{I}_{C_j}^{\mathcal{G}_r}$ that will be used for the negotiation at $r$ round. If $ACK_k = A$, the leader decides whether to accept or to reject the offer of resource allocation $\mathcal{G}_{r-1}(v(C_j \cup \{k\}))$ made by the user $k$ at $(r-1)$ negotiation round. The leader notifies its decision to the user by sending $ACK_{L_j}$ with accept $(A)$ if the offered resource allocation does not decrease the coalition value or reject $(R)$ if it does. Specifically, $ACK_{L_j} = A$ if

$$\Delta v_k(C_j) \triangleq v(C_j \cup \{k\}) - v(C_j) \geq 0 \tag{3}$$

where $v(C_j \cup \{k\}) = \sum_l [\mathcal{G}(v(C_j \cup \{k\}))]_l$. Note that $\Delta v_k(C_j)$ can be interpreted as the *marginal contribution*[5] of user $k$ to coalition $C_j$ [14], [16]. The leader also sends another available offer of the channel sharing strategy $\mathcal{G}_r$ and the corresponding information $\mathbf{I}_{C_j}^{\mathcal{G}_r}$ for $\mathcal{G}_r$ to user $k$.

•*Resource Allocation Offers From User $k$ (In Line 10–19):* Based on the offered strategy $\mathcal{G}_r$ and the information $\mathbf{I}_{C_j}^{\mathcal{G}_r}$, user $k$ can compute the resource allocation, i.e.,

$$\mathcal{G}_r(v(C_j \cup \{k\})) = \left([\mathcal{G}_r(v(C_j))]_1, \ldots, [\mathcal{G}_r(v(C_j))]_{m_j}, [\mathcal{G}_r(v(C_j))]_k\right)$$

where $[\mathcal{G}_r(v(C_j))]_k$ denotes the user $k$'s utility derived by strategy $\mathcal{G}_r$. Note that the perceived utility of user $k$ can be affected by the elapsed time for the strategy negotiation, which can be measured by its *patience factor* [14]. This is denoted by $\delta_k^{t(r)} (\geq 0)$ for user $k$ and it is a non-increasing function of elapsed time $t(r)$ up to $r$ rounds. The patience factor can be determined based on the delay sensitivity determined by the application. The perceived utility of user $k$ for strategy negotiation at time $t(r)$ is determined as $\delta_k^{t(r)} \cdot [\mathcal{G}_r(v(C_j))]_k$. The offered strategy $\mathcal{G}_r$ is acceptable for user $k$ if the derived utility guarantees the minimum required utility and does not decrease its utility (in line 15). If $\mathcal{G}_r$ is acceptable, user $k$ acknowledges its decision by sending $ACK_k = A$ with the resource allocation. Otherwise, it only sends $ACK_k = R$. Note that user $k$ can also acknowledge that the available time for channel sharing strategies is expired by sending $ACK_k = T$ if the elapsed time $t(r)$ is large enough such that $\delta_k^{t(r)} \approx 0$, leading to $\delta_k^{t(r)} \cdot [\mathcal{G}_r(v(C_j))]_k \approx 0$, or $t(r)$ exceeds the negotiation time limit $T_k^A$, i.e., $t(r) \geq T_k^A$.

After the negotiation with coalition $C_j$, user $k$ can identify the best channel sharing strategy $\mathcal{G}_j^*$ among the offered strategies by the leader. Finally, the user can identify all the best channel sharing strategies $\boldsymbol{\mathcal{G}}_{\boldsymbol{\theta}_k}^* = \{\mathcal{G}_j^* | j \in \boldsymbol{\theta}_k\}$ from its available coalitions. Based on $\boldsymbol{\mathcal{G}}_{\boldsymbol{\theta}_k}^*$, user $k$ will select and join a coalition based on Procedure 1.

### C. Analysis of Generic Communication Cost

In this section, we determine generic communication costs (overheads) incurred by the information exchanges between a leader and an incoming user for the proposed negotiation strategy.[6] We assume that the communication cost is represented by the total volume of messages exchanged during the leader selection and negotiation period. Furthermore, we

[5]The marginal contribution of user $k$ with respect to set $p_\pi^k$ is defined as [16] $\Delta v_k(p_\pi^k) \triangleq v(p_\pi^k \cup \{k\}) - v(p_\pi^k)$, where $\pi$ denotes a permutation on a set of users and $p_\pi^k = \{l : \pi(k) > \pi(l)\}$ denotes the set of users preceding user $k$ in order.

[6]Note that future research should explicitly consider the resulting overhead incurred by implementing the proposed solutions using specific protocols.

TABLE I
INFORMATION EXCHANGES AND CHARACTERISTICS OF PROPOSED CHANNEL SHARING STRATEGIES

| Exchanged Information of User $k$ ($\hat{\mathbf{I}}_k$) | Characteristics of Channel Sharing Strategies ($\mathcal{G}$) | Section |
|---|---|---|
| $\emptyset$ (No information exchange) | Random channel access | - |
| $\mathbf{I}_k^{FCFS} \triangleq \left\{\mathbf{R}_k^M(\boldsymbol{\theta}_k), \mathbf{I}_{TS_k}^{FCFS} = \{\Psi_k\}\right\}$ | First come, first served | IV-A |
| $\mathbf{I}_k^{SV} \triangleq \left\{\mathbf{R}_k^M(\boldsymbol{\theta}_k), \mathbf{I}_{TS_k}^{SV} = \{\Psi_k, U_k(g_k(\Psi_k))\}\right\}$ | Incoming order independent | IV-B |
| $\mathbf{I}_k^{BS} \triangleq \left\{\mathbf{R}_k^M(\boldsymbol{\theta}_k), \mathbf{I}_{TS_k}^{BS} = \{\Psi_k, U_k(g_k(\Psi_k)), U_k^m\}\right\}$ | Guaranteed minimum required utility | IV-C |

assume that the transmission time for each message is proportional to the size of the message and the number of message exchanges, divided by the transmission rate of the channel, i.e.,

$$d_{MSG} = \frac{\{size(MSG) \times num(MSG)\}}{rate_c}$$

where $size(MSG)$, $num(MSG)$, and $rate_c$ denote the size of messages, the number of message exchanges, and data transmission rates of the channel, respectively.

*1) Selecting a Leader:* To select a leader in a coalition $C_j$, information about the possible candidates (i.e., coalition members) needs to be exchanged. The induced delays can be expressed as

$$d_{LS} = d_{MSG} \times m_j$$

where $m_j$ denotes the number of users in $C_j$. Note that the information included in message exchanges depends on deployed leader selection schemes (see, e.g., [19], [20]), and determines the parameters $size(MSG)$ and $num(MSG)$.

*2) Collecting Resource Requirements:* The selected leader collects the information about the resource requirements of coalition members, thereby starting to negotiate the channel sharing strategies. Hence, the incurred delay is expressed as

$$d_{CM} = \frac{\{size(MSG) \times m_j\}}{rate_c}.$$

The exchanged messages contain different information about the resource requirements of users depending on the deployed channel sharing strategies. Hence, $size(MSG) = \sum_{l \in C_j} size(\hat{\mathbf{I}}_l)$.

*3) Negotiating Resource Sharing Strategies:* While negotiating the channel sharing strategies, the leader and the newly joining user need to exchange messages in each round. Hence, the corresponding delay is expressed as

$$d_{NS} = \frac{1}{rate_c} \sum_{r=1}^{r_{MAX}} \Big[ (size(\{ACK_{L_j}, \mathcal{G}_r, \hat{\mathbf{I}}_{C_j}^{\mathcal{G}_r}\}) + size(\{\mathcal{G}_r(v(C_j)), ACK_k\}) \Big]$$

where $r_{MAX}$ denotes the maximum number of rounds for the negotiation of channel sharing strategies and $\hat{\mathbf{I}}_{C_j}^{\mathcal{G}_r}$ represents the exchanged information at round $r$.

*4) Determining Resource Allocations:* Based on the determined channel sharing strategy and the corresponding resource allocations, the leader announces the message for the resulting resource allocation to coalition members. Thus

$$d_{RA} = \frac{\{size([\mathcal{G}(v(C_j)]_l) \times m_j\}}{rate_c}$$

where $[\mathcal{G}(v(C_j)]_l$ denotes the allocated utility to user $l$ derived by strategy $\mathcal{G}$.

Therefore, the total delay due to the communication cost is expressed as

$$d_{COMM} = d_{LS} + d_{CM} + d_{NS} + d_{RA}. \quad (4)$$

## IV. INFORMATION-DRIVEN RESOURCE NEGOTIATION STRATEGIES

In this section, we discuss several channel sharing strategies based on the information exchanged among the multimedia users. We study the performance of the channel sharing strategies in terms of the derived multimedia utility and the computational complexity required to implement them. In particular, we focus on the resource allocation process for an individual user $k$. We briefly summarize the characteristics of the strategies ($\mathcal{G}$) based on information exchanges ($\hat{\mathbf{I}}_k$) in Table I.

### A. FCFS Channel Sharing Strategy

The channels can be shared based on a FCFS strategy, which is often used in practice [18], [21]. This strategy can be deployed if the information exchanged among users includes the maximum achievable rates and the TSPECs of users. Hence, the necessary information that needs to be available for user $k$ in coalition $C_j$ is given by $\mathbf{I}_{C_j}^{FCFS} \triangleq \left\{R_{jl}^M, \mathbf{I}_{TS_l}^{FCFS} = \{\psi_l\} \middle| l \in C_j, \psi_l \in \Psi_l\right\}$, where TSPEC $\mathbf{I}_{TS_l}^{FCFS}$ specifies only the rate requirement. This information is provided by the leader of $C_j$. Then, user $k$ can compute the rates achieved by joining $C_j$. The maximum rate that user $k$ can achieve is expressed as

$$\left(1 - \sum_{l \in C_j} \tau_{jl}\right) \cdot R_{jk}^M \quad (5)$$

where $\tau_{jl} = g_l(\psi_l) / R_{jl}^M$ denotes the allocated TXOP to user $l$ deploying its TSPEC $\psi_l$ in $C_j$. Hence, user $k$ can derive the maximum utility $U_k(g_k(\psi_k))$ if a TSPEC $\psi_k \in \Psi_k$ that corresponds to effective rate $g_k(\psi_k) = \left(1 - \sum_{l \in C_j} \tau_{jl}\right) \cdot R_{jk}^M$ is available to user $k$. If user $k$ has a TSPEC $\psi_k \in \Psi_k$ that corresponds to effective rate $g_k(\psi_k) < \left(1 - \sum_{l \in C_j} \tau_{jl}\right) \cdot R_{jk}^M$, the TSPEC determines the maximum achievable rate and the utility.

As shown in (5), the computational complexity required to compute the resource allocation can be estimated by $O(m_j)$

flops (floating point operations),[7] which is linearly increasing with the number of users in the coalitions. Hence, the time required for resource allocation based on FCFS increases linearly with respect to the number of users $m_j$ in $C_j$.

Note that the derived utility $U_k(g_k(\psi_k))$ can be viewed as the marginal contribution of user $k$ to coalition $C_j$, since $v(C_j)$ is defined as the aggregated utility derived in $C_j$ based on the FCFS strategy, i.e.,

$$\Delta v_k(C_j) = \sum_{l \in C_j \cup \{k\}} U_l(g_l(\psi_l)) - \sum_{l \in C_j} U_l(g_l(\psi_l)) = U_k(g_k(\psi_k)). \quad (6)$$

Even though the FCFS strategy can consider the impact on utility with a lower computational complexity, the resource allocation based on this strategy depends largely on the order in which the users join the coalitions. Hence, this resource allocation scheme is unfair towards users, who may have equal rights to network resources, but simply join a coalition at a later time. While this unfairness can be resolved by using centralized *rate-based* fair resource allocation schemes (e.g., [4], [5]), such strategies do not consider the resulting impact on utility. Alternatively, this unfairness can be resolved by considering the users' marginal contributions *averaged* over all possible orders of the users joining the coalition.

### B. Incoming Order Independent Channel Sharing Strategy

For users having equal rights to access the network resources, the TXOP allocation should depend on their contribution to the coalition value, and not the order in which they join the coalitions. Hence, users can negotiate the TXOP division based on their average marginal contributions to the coalition value. In order to determine the coalition value, the users must exchange information about their achievable utilities. Hence, the information provided by a leader to user $k$ is given by $\mathbf{I}_{C_j}^{SV} \triangleq \left\{R_{jl}^M, \mathbf{I}_{TS_l}^{SV} = \{\psi_l, U_l(g_l(\psi_l))\} \middle| l \in C_j, \psi_l \in \Psi_l\right\}$, where TSPEC specifies the rate requirement and its utility impact. Based on this information, user $k$ can compute the resource allocation, such that the users in coalition $C_j$ can derive the utility corresponding to their averaged marginal contribution, i.e.,

$$U_l(g_l(\psi_l)) = \left\{\frac{1}{(m_j+1)!} \sum_{\check{C} \in \Pi(C_j \cup \{k\})} \Delta v_l(\check{C})\right\} \quad (7)$$

for all $l \in C_j \cup \{k\}$, where $\Pi(C_j \cup \{k\})$ denotes the set of all permutations on $C_j \cup \{k\}$. Note that this strategy is based on the Shapley value [23] in coalition game theory. Its fairness properties are investigated in [15], [16], and [24]. The complexity for computing (7) is $O(m_j!)$ flops. Thus, the time required for resource allocation based on the Shapley value increases factorially with respect to the number of users $m_j$ in coalition $C_j$.

Although the channel sharing strategy based on the Shapley value can resolve the problem of dependency on the order in which the users join coalitions, two issues still need to be addressed. First, the computational complexity increases factorially with the number of users in a coalition, making it impractical to compute (7) when there are many users. However, the number of users in the coalitions can be limited to a reasonably small number, as the users can leave or switch coalitions if they become congested. Moreover, the level of TSPEC granularity (i.e., $H_k$) can also be adjusted to reduce the communication overhead and computational complexity.

Another issue is that of *infeasible* orderings, where some users' minimum required utilities are not satisfied. These orderings are included in (7), and can lead to inefficient resource utilization. As shown in [15], the sum of utilities achieved by the channel sharing strategy based on the Shapley value is the same as the average coalition value for all permutations on a coalition, i.e.,

$$\sum_{l \in C_j} \left\{\frac{1}{m_j!} \sum_{\check{C} \in \Pi(C_j)} \Delta v_l(\check{C})\right\} = \frac{1}{m_j!} \sum_{\check{C} \in \Pi(C_j)} v(\check{C})$$

where $\Pi(C_j)$ denotes the set of all permutations on coalition $C_j$. Since the channel sharing strategy based on the Shapley value considers $\Pi(C_j)$, which can include infeasible orderings, it can lead to inefficient channel utilization. To guarantee a minimum required utility for multimedia users, additional information needs to be exchanged. We discuss this in the next section.

### C. Channel Sharing Strategy Considering the Minimum Utility Requirements

For multimedia users, ensuring the minimum required utility is important. If the exchanged information includes the minimum required utility, then users can negotiate the TXOP division while explicitly considering the minimum required utility. Hence, the information provided by a leader to user $k$ is given by $\mathbf{I}_{C_j}^{BS} \triangleq \left\{R_{jl}^M, \mathbf{I}_{TS_l}^{BS} = \{\psi_l, U_l(g_l(\psi_l)), U_l^m\} \middle| l \in C_j, \psi_l \in \Psi_l\right\}$.

The channel sharing strategy based on the Shapley value discussed in Section IV-B can be improved by considering only *feasible* orderings, where the utility achieved by all users satisfies the users' minimum required utility. Hence, user $k$ can compute the resource allocation such that the users can derive their utility based on their averaged marginal contribution in the feasible orderings, i.e.,

$$U_l(g_l(\psi_l)) = \left\{\frac{1}{|\Pi^*(C_j \cup \{k\})|} \sum_{\check{C} \in \Pi^*(C_j \cup \{k\})} \Delta v_l(\check{C})\right\}$$

for all $l \in C_j \cup \{k\}$, where $\Pi^*(C_j \cup \{k\}) \subseteq \Pi(C_j \cup \{k\})$ denotes the set of all feasible permutations on $C_j \cup \{k\}$. Therefore, this channel sharing strategy enables the users to negotiate TXOP division based on their average marginal contributions, while explicitly ensuring the minimum required utility. However, because this channel sharing strategy is not guaranteed to utilize all TXOPs (i.e., it is not Pareto optimal [22]), it becomes an inefficient channel sharing strategy (see the Appendix ).

Alternatively, user $k$ can allocate the resources based on predetermined fairness such that the users in a coalition can 1) utilize all available TXOPs, 2) ensure their minimum required utility, and 3) fairly allocate the available TXOPs. First, user $k$ considers all sets of feasible TXOP divisions $(\tau_{j1}, \ldots, \tau_{jm_j}, \tau_{jk})$ for $0 \le \tau_{jl} \le 1$, $l \in C_j \cup \{k\}$ and

[7]Flop counts can give a good estimate of the computation time of a numerical algorithm, and how the time grows with an increasing problem size [22].

$\sum_{l\in C_j\cup\{k\}} \tau_{jl} \leq 1$ in coalition $C_j \cup \{k\}$. Then, the user identifies the feasible utility set $\mathbf{S}_j$, expressed as

$$\mathbf{S}_j = \left\{ \mathbf{U}_j = \Big( U_1(g_1(\psi_1)), \ldots, U_{m_j}\left(g_{m_j}\left(\psi_{m_j}\right)\right), U_k(g_k(\psi_k)) \Big) \,\middle|\, \sum_{l\in C_j\cup\{k\}} \tau_{jl} \leq 1, \psi_l \in \Psi_l \right\}$$

where $g_l(\psi_l) \leq \tau_{jl}\cdot R_{jl}^M$ for $l \in C_j\cup\{k\}$. A set of the minimum required utilities of the users in coalition $C_j \cup \{k\}$ is denoted by $\mathbf{d}_j = (d_1, \ldots, d_{m_j}, d_k) \in \mathbb{R}^{m_j+1}$, where $d_l = U_l^m = U_l\left(g_l\left(\psi_l^{\min}\right)\right)$ for $l \in C_j \cup \{k\}$ and $g_l\left(\psi_l^{\min}\right) = \tau_{jl}^{\min} \cdot R_{jl}^M$ is the rate required to guarantee the minimum utility $U_l^m$. Since all TXOPs need to be allocated (i.e., $(\tau_{j1}, \ldots, \tau_{jm_j}, \tau_{jk})$ for $0 \leq \tau_{jl} \leq 1$ and $\sum_{l\in C_j\cup\{k\}} \tau_{jl} = 1$ ), only the *boundary* of $\mathbf{S}_j$, denoted by $\partial\mathbf{S}_j \in \mathbf{S}_j$, is considered. Then, the users only consider the set of achievable utilities that guarantee their minimum utilities in $\partial\mathbf{S}_j$, which is denoted by $\mathbf{B}_j$:

$$\begin{aligned}\mathbf{B}_j &= \{\mathbf{U}_j \,|U_l \geq d_l,\ \forall\, l \in C_j \cup \{k\}\} \cap \partial\mathbf{S}_j \\ &= \left\{ \mathbf{U}_j \,\middle|\, \tau_{jl} \geq \tau_{jl}^{\min},\ \forall\, l \in C_j \cup \{k\}, \sum_{l\in C_j\cup\{k\}} \tau_{jl} = 1 \right\}.\end{aligned}$$

A unique utility pair in the set $\mathbf{B}_j$ can be determined based on the fairness rules, which ensure that certain relationships between the utilities of the multimedia users are fulfilled. In the game theoretic literature, these relationships are called *axioms of fairness* and the resulting solution is the *axiomatic bargaining solution* [14]. The axiomatic bargaining solution is a function $\phi : (\mathbf{S}_j, \mathbf{d}_j) \to \mathbb{R}^{m_j+1}$, defined as

$$\phi(\mathbf{S}_j, \mathbf{d}_j) = (\phi_1(\mathbf{S}_j, \mathbf{d}_j), \ldots, \phi_{m_j}(\mathbf{S}_j, \mathbf{d}_j), \phi_k(\mathbf{S}_j, \mathbf{d}_j)) \in \mathbf{B}_j$$

where $\phi_l(\mathbf{S}_j, \mathbf{d}_j)$ denotes the derived utility for user $l$, i.e., $U_l(g_l(\psi_l)) = \phi_l(\mathbf{S}_j, \mathbf{d}_j)$. Therefore, given the feasible utility set $\mathbf{S}_j$ and the set of minimum required utilities $\mathbf{d}_j$ associated with the coalition $C_j \cup \{k\}$, the coalition value $v(C_j \cup \{k\})$ can be expressed as the sum of utilities determined by the deployed bargaining solutions, i.e.,

$$v(C_j \cup \{k\}) = \sum_{l\in C_j\cup\{k\}} \phi_l(\mathbf{S}_j, \mathbf{d}_j).$$

Identifying the complete feasible utility set $\mathbf{S}_j$ for $j \in \boldsymbol{\theta}_k$ dominates the implementation complexity of these axiomatic bargaining solutions. If only quantized service intervals with the step size $\Delta t\,(\leq t_{SI})$ are considered, the computational complexity required for identifying the complete feasible utility set can be estimated as $O\left((t_{SI}/\Delta t)^{m_j}\right)$ flops. Hence, the time required for resource allocation based on the bargaining solutions increases exponentially with respect to the number of users $m_j$ in coalition $C_j$. Fortunately, as we showed in our previous work [25], the axiomatic bargaining solutions can be obtained without completely identifying the feasible utility set, thereby significantly reducing the computational complexity [22]. Moreover, the TSPEC granularity can also be adjusted to reduce the computational complexity required to form the feasible utility.

Alternatively, multimedia users can be classified into several classes (similar to the notion of *profiles* and *levels* in MPEG standards [26]) based on their spatio-temporal video resolutions and associated bit rates. Thus, a leader can consider all users with similar resource requirements as one class of users when it negotiates channel sharing strategies and resource allocations. By limiting the number of user classes to a reasonably small number (e.g., ten or less), the leader can perform resource allocation to each class. After dividing resources among classes of users, the allocated resources can be equally split among the individual users in each class, as the resource requirements of the users in the same class are similar.[8]

In this paper, we consider the Kalai–Smorodinsky bargaining solution (KSBS) [27] as it can provide a fair division of resources for autonomous multimedia users [25].

## V. Convergence Analysis

The system dynamics can be induced by users that join, leave, or switch coalitions, and can be measured in terms of the variation in coalition values. The term "system" represents the set of all the network resources (channels). Hence, system dynamics can be represented by the variation in *system utility*, defined as

$$\Delta v(C) = v(C^+) - v(C) \tag{8}$$

where $C = \bigcup_{j=1}^{N} C_j$ denotes the set of all coalitions (i.e., all the channels) and $v(C) = \sum_{j=1}^{N} v(C_j)$ represents the system utility. The notation $C^+$ is used to denote the updated $C$ after users join or switch coalitions. As discussed earlier, $\Delta v(C)$ can also be interpreted as the marginal contribution of incoming users to system $C$. Hence, $\Delta v(C)$ can represent the impact of the interactions between the users and the coalitions on the system utility. We consider the following cases.

### A. Impact of Incoming Users

If there are a few users in the system (i.e., less congested system), additional incoming users to the system can increase the system utility (i.e., $\Delta v(C) \geq 0$), as the system has enough network resources to support the users. However, if the system is already congested due to many users, additional incoming users to the system can decrease the system utility (i.e., $\Delta v(C) \leq 0$). More specifically, if user $k$ joins coalition $C_j$ in the system, the variation in system utility can be expressed as $\Delta v(C) = \Delta v_k(C_j) = v(C_j \cup \{k\}) - v(C_j)$. If

$$\Delta v(C) > 0 \Leftrightarrow U_k(g_k(\psi_k)) > 0 \tag{9}$$

then the system utility is *aligned* with the derived utility of incoming user $k$. For example, a centralized network with an admission control policy that allows only the users which can improve the system utility to join the system can ensure the condition shown in (9). Hence, if the system utility and incoming users' derived utility are aligned, a higher system utility is achieved as more users join the network. Furthermore, if the

[8]If the computation complexity is still concern, a suboptimal solution, where a user and a coalition determine a resource allocation by simply selecting a precomputed resource allocation from a set of predetermined values, can be used.

system utility improvement and incoming users' derived utility are the same, i.e.,

$$\Delta v(C) = v(C_j \cup \{k\}) - v(C_j) = U_k\left(g_k\left(\psi_k\right)\right) \quad (10)$$

then the impact of incoming users on the system utility is exactly represented by the incoming users' derived utility. Hence, if (10) holds for deployed channel sharing strategies, then a stationary distribution of users across the channels in the system is guaranteed by considering $v(C)$ as a potential function [28].

### B. Impact of Switching Coalitions

Users switch coalitions if they can improve their utility. However, the impact of the users' switching coalitions on the system utility can be varied depending on the alignment with the derived utility of the user. Specifically, if user $k$ switches from coalition $j$ to coalition $j'$, the impact of this change can be expressed using the marginal contribution as $\Delta v(C) = v(C^+) - v(C)$, where $C^+ = C_1 \cup \cdots \cup (C_j \backslash \{k\}) \cup \cdots \cup (C_{j'} \cup \{k\}) \cup \cdots \cup C_N$ and $C = C_1 \cup \cdots \cup C_j \cup \cdots \cup C_{j'} \cup \cdots \cup C_N$. If $\Delta v(C) > 0$, then user $k$'s switching coalition improves its derived utility as well as the system utility. However, if $\Delta v(C) < 0$, user $k$'s switching coalition improves its derived utility but decreases the system utility. If the variation in system utility is the same as the variation in user $k$'s utility, i.e.,

$$\Delta v(C) = U_k\left(g_k\left(\psi'_k\right)\right) - U_k\left(g_k\left(\psi_k\right)\right) \quad (11)$$

then $v(C)$ is a potential function, thereby ensuring a stationary distribution of users in the system.

As an illustrative example, if the FCFS channel sharing strategy is deployed in each coalition, then conditions in (10) and (11) are satisfied as shown in (6). Hence, a stationary distribution of the users can be guaranteed. We note that the other proposed channel sharing strategies based on the Shapley value or bargaining solutions (i.e., the KSBS) do not guarantee a stationary distribution of users in the system. This can be easily shown by a simple counterexample.

## VI. Performance Analysis of the Channel Sharing Strategies

In this section, we analyze the discussed channel sharing strategies by comparing them in terms of the average utility deviation.

### A. Performance Measure for Channel Sharing Strategies

To quantify the performance of the considered channel sharing strategies, we propose a performance measure called the *average utility deviation (AUD)*. The AUD is the average distance between the utility determined by a channel sharing strategy and a *reference utility*, which is the uniquely determined optimal solution based on fairness axioms. Hence, AUD shows how far the derived utility is from the reference utility. However, as discussed in Section IV-C, it requires a large amount of information exchanges (i.e., communication overhead) and high computational complexity to determine a unique and optimal fair solution based on several fairness axioms. However, the optimal solution can serve as a theoretical bound for benchmarking the performance of the various investigated channel sharing strategies in terms of the AUD.

Specifically, for achieved utility $\mathbf{U}_j = \left(U_1(g_1(\psi_1)), \ldots, U_{m_j}(g_{m_j}(\psi_{m_j}))\right)$ determined by a channel sharing strategy $\mathcal{G}$ in coalition $C_j$ and a reference utility $\mathbf{U}_j^R = (U_{j1}^R, \ldots, U_{jm_j}^R)$, the AUD is expressed as

$$AUD_j = \frac{1}{m_j} \sum_{l=1}^{m_j} \left| U_{jl}^R - U_l(g_l(\psi_l)) \right| \triangleq \frac{\|\mathbf{U}_j^R - \mathbf{U}_j\|_1}{m_j}.$$

We assume that the reference utility $\mathbf{U}_j^R$ is determined based on the finest-granularity TSPECs (i.e., $|\Psi_k| = H_k$ with large $H_k$) for all $k \in C_j$, and the global information exchanges $\mathbf{I}_G$ (i.e., all the information required for the resource negotiation). Note that the AUD decreases as the utility achieved by a deployed channel sharing strategy approaches the reference utility. Since the reference utility is obtained based on the global information, it can be expected that more information exchanges can lead to smaller AUD. The impact of the additional information exchanges on the AUD is analytically quantified by considering the value of the information, discussed in the next section.

### B. Value of Information Exchanges

In this section, we analytically quantify the value of information in terms of the AUD for several cases. As the reference utility is obtained by using the global information, the value of information represents the distance between the utility achieved based on the exchanged information and the reference utility. The minimum value of AUD given the exchanged information $\hat{\mathbf{I}}_{C_j}$ in network resource $j$ is denoted by $V(\hat{\mathbf{I}}_{C_j})$, expressed as

$$V(\hat{\mathbf{I}}_{C_j}) = -\min_{\mathcal{G} \in \hat{\boldsymbol{\mathcal{G}}}_j} \{AUD_j\} = -\min_{\mathcal{G} \in \hat{\boldsymbol{\mathcal{G}}}_j} \left\{ \frac{1}{m_j} \|\mathbf{U}_j^R - \mathbf{U}_j\|_1 \right\}$$

where $\hat{\boldsymbol{\mathcal{G}}}_j$ denotes the set of available channel sharing strategies for the exchanged information $\hat{\mathbf{I}}_{C_j}$, and $\mathbf{U}_j$ is the utility determined by $\mathcal{G}$. Using $V(\cdot)$, we define the value of information of $I$ with respect to information $\hat{\mathbf{I}}$ using the marginal contribution of information $I$ as

$$\Delta V_I(\hat{\mathbf{I}}) = V(\hat{\mathbf{I}} \cup I) - V(\hat{\mathbf{I}}) \quad (12)$$

which measures how much information $I$ can move the derived utility $\mathbf{U}_j$ closer to the reference utility. Note that $\Delta V_I(\hat{\mathbf{I}}) = 0$ represents the case when additional information exchange does not improve the derived utility. For example, if $I$ is irrelevant information for channel sharing strategies, then $\Delta V_I(\hat{\mathbf{I}}) = 0$. The value of information will be used to analyze and compare the discussed channel sharing strategies.

### C. Analytical Comparison Between Channel Sharing Strategies

In the following analysis, we assume that video sequences are classified into two types: high-bandwidth sequences and low-bandwidth sequences. The same type sequences are assumed to have the same $U^m$ and $U^M$ (i.e., $U_l^m = U_{l'}^m$ and $U_l^M = U_{l'}^M$ for the same types of users $l$ and $l'$), and similar rate-distortion performance. We assume that $U^M$ can be always achieved if only one user is in a coalition. We also assume that the finest-granularity TSPECs are available, thereby supporting any transmission rates between the minimum and maximum operational rate points.

As shown in Table I, the channel sharing strategy based on the KSBS requires the largest amount of information exchanges out of the discussed channel sharing strategies. Hence, we assume that $\mathbf{U}_j^R$ is determined by the KSBS with the finest-granularity TSPECs and $\mathbf{I}_G$. Since the channel sharing strategies based on the FCFS or the Shapley value require different information exchanges (i.e., $\mathbf{I}^{FCFS}$ and $\mathbf{I}^{SV}$), we focus on comparing both strategies in terms of the value of information. We consider the following cases.

*1) Same Types of Applications With TSPECs Supporting $U^M$:* Suppose $m_j$ users are the same types of applications in coalition $C_j$. We assume that the TSPECs that support $U^M$ are available for the users. Based on the FCFS channel sharing strategy, if user $k$ joins the coalition first, then the achieved utility is given by $\mathbf{U}_j^{FCFS} = \underbrace{(0,\ldots,0,U^M,0,\ldots,0)}_{m_j}$, where only user $k$ can achieve $U^M$ among $m_j$ users. The channel sharing strategy based on the Shapley value allocates the available TXOPs such that $\mathbf{U}_j^{SV} = ((m_j-1)!/m_j!)\underbrace{(U^M,\ldots,U^M)}_{m_j} = (1/m_j)\mathbf{U}^M$, where $\mathbf{U}^M = \underbrace{(U^M,\ldots,U^M)}_{m_j}$. Finally, since the reference utility $\mathbf{U}_j^R$ is obtained by the channel sharing strategy based on the KSBS

$$\mathbf{U}_j^R = \mathbf{U}_j^{KSBS} = \mathbf{d} + \alpha\cdot(\mathbf{U}^M - \mathbf{d}) \tag{13}$$

where $\mathbf{d} = (U^m,\ldots,U^m)$ and $\alpha\,(0 \le \alpha \le 1)$ indicates a constant uniquely determined by the KSBS (see, e.g., [25] for more details). Note that $\alpha$ is determined such that the all available TXOPs are allocated. Since $\mathbf{d}$ can be expressed as $\mathbf{d} = U^m/U^M \cdot \mathbf{U}^M$, (13) can be rewritten as

$$\mathbf{U}_j^R = \mathbf{U}_j^{KSBS} = \gamma\cdot\mathbf{U}^M \tag{14}$$

where $U^m/U^M \le \gamma \le 1$. Hence, the value of information $I = \{U_l(g_l(\Psi_l))\,|l\in C_j\}$ with respect to $\hat{\mathbf{I}}_{C_j} = \{\mathbf{I}_l^{FCFS}\,|l\in C_j\}$ is given by

$$\begin{aligned}\Delta V_I(\hat{\mathbf{I}}_{C_j}) &= -\frac{1}{m_j}\left\{\|\mathbf{U}_j^R - \mathbf{U}_j^{SV}\|_1 - \|\mathbf{U}_j^R - \mathbf{U}_j^{FCFS}\|_1\right\}\\ &= -\frac{1}{m_j}\left\{\left\|\gamma\cdot\mathbf{U}^M - \frac{1}{m_j}\mathbf{U}^M\right\|_1\right.\\ &\qquad\left.-\left\|\gamma\cdot\mathbf{U}^M - (0,\ldots,0,U^M,0,\ldots,0)\right\|_1\right\}\\ &= -\left\{\left(\gamma - \frac{1}{m_j}\right)\right\}U^M + \frac{1}{m_j}\{\gamma\cdot(m_j-1)\\ &\qquad + |\gamma-1|\}U^M = \frac{2}{m_j}(1-\gamma)U^M \ge 0\end{aligned} \tag{15}$$

if $\gamma \ge 1/m_j$. Therefore, if $m_j\cdot U^m \ge U^M$, implying that the sum of minimum required utilities for all users in coalition $C_j$ is larger than the maximum achievable utility, we have $\Delta V_I(\hat{\mathbf{I}}_{C_j}) \ge 0$ (i.e., $AUD_j^{SV} \le AUD_j^{FCFS}$). Note that acceptable video qualities are usually between 27 and 40 dB. Hence, for $U^m = 27$ dB and $U_M = 40$ dB, this condition is always fulfilled as long as more than two users are in the coalition (i.e., $m_j \ge 2$).

In conclusion, if a network resource is shared by the same types of users with the TSPECs that can support the maximum utility, the channel sharing strategy based on the Shapley value always outperforms the FCFS strategy in terms of the AUD performance. In other words, the additional information exchange $I$ improves the AUD performance.

*2) Same Types of Applications With Limited TSPECs Supporting $U^M$:* Suppose $m_j$ users are the same types of applications in coalition $C_j$. Due to the limited TSPEC availability, we assume that user $k$ can derive a predetermined maximum rate $g_k(\psi_k^{MAX})$, which corresponds to the available TSPEC $\psi_k^{MAX} \in \Psi_k$. We assume that the supported maximum rate is $g_k(\psi_k^{MAX})(\le R_{jk}^M)$ that corresponds to $U_k^M$. Hence, the achievable utility for rate $g_k(\psi_k^{MAX})$ is denoted by $U_k^M = \beta_k\cdot U^M$, where $0\le\beta_k\le 1$. Note that the required TXOP for $\psi_k^{MAX}$ is denoted by $\tau_{jk}^{MAX}$, where $g_k(\psi_k^{MAX}) = \tau_{jk}^{MAX}\cdot R_{jk}^M$.

Suppose that $\beta_l \le \alpha$ for all the users $l\in C_j$ (i.e., network resource $j$ is not congested). Thus, $\sum_{l=1}^{m_j}\tau_{jl}^{MAX}\le 1$, implying that the available network resources are enough to support the network resources requested by all the users in $C_j$. Hence, in this case, the utility achieved by the FCFS strategy does not depend on the orders in which users join the coalitions. Hence

$$\mathbf{U}_j^{FCFS} = (\beta_1U^M, \beta_2U^M,\ldots,\beta_{m_j}U^M). \tag{16}$$

Since $\mathbf{U}_j^{FCFS}$ is now order-independent, we have $\mathbf{U}_j^{SV} = \mathbf{U}_j^{FCFS}$. Thus

$$\begin{aligned}&\|\mathbf{U}_j^R - \mathbf{U}_j^{FCFS}\|_1\\ &\quad= \left\|\alpha\cdot(U^M,\ldots,U^M) - (\beta_1U^M,\beta_2U^M,\ldots,\beta_{m_j}U^M)\right\|_1\\ &\quad= \sum_{l=1}^{m_j}(\alpha-\beta_l)U^M = \left\|\mathbf{U}_j^R - \mathbf{U}_j^{SV}\right\|_1.\end{aligned} \tag{17}$$

Therefore, $\Delta V_I(\hat{\mathbf{I}}_{C_j}) = 0$ (i.e., $AUD_j^{FCFS} = AUD_j^{SV} \ge AUD_j^{KSBS}$). If $\beta_1 = \cdots = \beta_{m_j} = \alpha$, then $AUD_j^{FCFS} = AUD_j^{SV} = AUD_j^{KSBS}$.

In conclusion, if a network resource is shared by the same types of users and their maximum desired network resources are supported, then the channel sharing strategies based on the Shapley value and the FCFS provide the same performance in terms of AUD. In other words, the additional information exchange $I$ does not improve resource negotiation if the network is not congested.

*3) Different Types of Applications:* We now consider a more general case, where users are transmitting different types of video sequences. We assume that the users' available TSPECs can support $U^M$. Among the $m_j$ users in coalition $C_j$, let $m_H$ and $m_L$ denote the number of users in high-bandwidth and low-bandwidth video sequences, respectively, i.e., $m_H + m_L = m_j$.

We denote the set of minimum required utilities of users as $\mathbf{d} = (d_1, \ldots, d_{m_j})$, where

$$d_l = \begin{cases} Q_L^m, & \{\text{if user } l \in \text{low-bandwidth sequences}\} \\ Q_H^m, & \{\text{if user } l \in \text{high-bandwidth sequences}\} \end{cases}$$

and the set of maximum achievable utilities as $\mathbf{U}^M = (U_1^M, \ldots, U_{m_j}^M)$, where

$$U_l^M = \begin{cases} U_L^M, & \{\text{if user } l \in \text{low-bandwidth sequences}\} \\ U_H^M, & \{\text{if user } l \in \text{high-bandwidth sequences}\} \end{cases}$$

for user $l$, $1 \leq l \leq m_j$. We assume that $U_L^M \geq U_H^M$ since low-bandwidth sequences can derive higher PSNR than high-bandwidth sequences given the same rate allocation. $\mathbf{U}^R$ is determined by the KSBS using (13).

If user $k$ with a low-bandwidth sequence joins the coalition first, then the achieved utility based on the FCFS is given by $\mathbf{U}_j^{FCFS} = \underbrace{(0, \ldots, 0, U_L^M, 0, \ldots, 0)}_{m_j}$. On the other hand, the utility achieved by the Shapley value can be expressed as $\mathbf{U}_j^{SV} = (1/m_j)\mathbf{U}^M$. Hence

$$\begin{aligned} \left\| \mathbf{U}_j^R - \mathbf{U}_j^{FCFS} \right\|_1 = & (m_L - 1)\left[(1-\alpha)U_L^m + \alpha U_L^M\right] \\ & + m_H\left[(1-\alpha)U_H^m + \alpha U_H^M\right] \\ & + (1-\alpha)(U_L^M - U_L^m) \end{aligned}$$

and

$$\begin{aligned} \left\| \mathbf{U}_j^R - \mathbf{U}_j^{SV} \right\|_1 = & m_L\left|(1-\alpha)U_L^m + \left(\alpha - \frac{1}{m_j}\right)U_L^M\right| \\ & + m_H\left|(1-\alpha)U_H^m + \left(\alpha - \frac{1}{m_j}\right)U_H^M\right|. \end{aligned}$$

If

$$\alpha \geq \max\left\{ \frac{\frac{U_L^M}{m_j} - U_L^m}{U_L^M - U_L^m}, \frac{\frac{U_H^M}{m_j} - U_H^m}{U_H^M - U_H^m} \right\} \tag{18}$$

then $\left\| \mathbf{U}_j^R - \mathbf{U}_j^{SV} \right\|_1 - \left\| \mathbf{U}_j^R - \mathbf{U}_j^{FCFS} \right\|_1 = -m_j \Delta V_I(\hat{\mathbf{I}}_{C_j})$ becomes

$$\begin{aligned} & -m_j \Delta V_I(\hat{\mathbf{I}}_{C_j}) \\ & \quad = 2(1-\alpha)U_L^m - U_L^M\left[\frac{m_L}{m_j} + 1 - 2\alpha\right] - \frac{m_H}{m_j}U_H^M. \end{aligned}$$

Moreover, if

$$\alpha \geq \frac{1}{2}\left(\frac{m_L}{m_j} + 1\right) \tag{19}$$

then $\Delta V_I(\hat{\mathbf{I}}_{C_j})$ becomes

$$\begin{aligned} & \Delta V_I(\hat{\mathbf{I}}_{C_j}) \\ & \leq -\frac{1}{m_j}\left\{2(1-\alpha)U_L^m - U_H^M\left[\frac{m_L}{m_j} + 1 - 2\alpha\right] - \frac{m_H}{m_j}U_H^M\right\} \\ & = -\frac{2}{m_j}(1-\alpha)(U_L^m - U_H^M). \end{aligned}$$

Hence, if

$$U_H^M \leq U_L^m \tag{20}$$

then $\Delta V_I(\hat{\mathbf{I}}_{C_j}) \leq 0$, implying $AUD_j^{FCFS} \leq AUD_j^{SV}$.

Similarly, if user $k$ with high-bandwidth sequence joins the coalition first and $\alpha \leq (1/2)(m_L/m_j + 1)$

$$\begin{aligned} & \Delta V_I(\hat{\mathbf{I}}_{C_j}) \\ & = -\frac{1}{m_j}\left\{\left\|\mathbf{U}^R - \mathbf{U}^{SV}\right\|_1 - \left\|\mathbf{U}^R - \mathbf{U}^{FCFS}\right\|_1\right\} \\ & \leq -\frac{1}{m_j}\left\{2(1-\alpha)U_H^m - U_L^M\left[\frac{m_H}{m_j} + 1 - 2\alpha\right] - \frac{m_L}{m_j}U_L^M\right\} \\ & = 2(1-\alpha)(U_H^m - U_L^M). \end{aligned}$$

Hence, if $U_L^M \leq U_H^m$, then $\Delta V_I(\hat{\mathbf{I}}_{C_j}) \leq 0$, implying $AUD_j^{FCFS} \leq AUD_j^{SV}$.

In conclusion, the AUD performance for different types of users depends on the order in which users join the coalitions. Even though the channel sharing strategy based on the Shapley value generally provides a better AUD performance than the FCFS strategy, the FCFS channel sharing strategy can provide better AUD performance if conditions (18)–(20) are fulfilled for a low-bandwidth sequence. However, note that some of these conditions such as (20) hold very rarely for multimedia applications, and thus, the channel sharing strategy based on the Shapley value can generally outperform the FCFS strategy. Nevertheless, in the case where the conditions are satisfied, the FCFS should be used for channel sharing strategy as this strategy requires less information exchanges and a lower computational complexity.

## VII. Simulation Results

### A. System Setup

We assess the performance of the considered channel sharing strategies in a network, where multiple multimedia users transmit their multimedia streams (e.g., video sequences). Multiple TSPECs for a video sequence are generated so that they can support the video transmission at various transmission rates. We assume that the supported transmission rates are uniformly separated within the range of the minimum and maximum rates [18]. The video sequences are encoded at specific target rates using on the H.264/AVC based video encoder. The video sequences are assumed to be classified as either high bandwidth-required sequences (e.g., *Mobile*) or low bandwidth-required sequences (e.g., *Foreman*, *Coastguard*, etc.). Non-multimedia data files can also be transmitted over the same network.

For the purpose of comparison, we also consider a centralized network, where a central resource coordinator manages the available network resources based on the discussed resource negotiation strategies. In this case, the central resource coordinator collects the information required for deployed resource negotiation strategies and allocates the network resources to the users. The central resource coordinator can deploy an admission control policy to ensure a certain level of system utility by allowing the users to join or switch coalitions. Hence, only user behavior that improves the system utility is allowed. We assume that the admission control policy is deployed in the centralized network.

### *B. Discussion of Multiple TSPECs and FCFS Channel Sharing Strategy*

In this section, we quantify the benefit from deploying multiple TSPECs for the channel sharing strategies. For illustration, we consider the FCFS channel sharing strategy discussed in Section IV-A. To focus on the channel utilization and the derived utility, we assume that the channel condition for each user is fixed, and only one coalition exists. We also assume that user 1 to user 6 transmit H.264 encoded video sequences of *Foreman* (CIF, 30 Hz), *Coastguard* (CIF, 30 Hz), *Mobile* (CIF, 30 Hz), *Foreman* (QCIF, 30 Hz), *Coastguard* (CIF, 15 Hz), and *Foreman* (CIF, 15 Hz), respectively.

Fig. 2 shows the resource utilization for the FCFS strategy with a fixed TSPEC and multiple TSPECs. In these simulations, we assume that each user has TSPECs that can support no more than the predetermined maximum utility. Each user's maximum utility is set to be

$$\mathbf{U}^M = (U_1^M, \ldots, U_6^M) \\ = (37\,\mathrm{dB}, 38\,\mathrm{dB}, 40\,\mathrm{dB}, 39\,\mathrm{dB}, 40\,\mathrm{dB}, 38\,\mathrm{dB}).$$

If only one TSPEC is available for the users, we assume that the TSPEC supports the maximum utility. We assume that multiple TSPECs are generated so that they can support 50 kbps rate intervals. The order in which the users join the coalitions are randomly determined in each experiment. As shown in the results, the resource utilization is obviously improved when multiple TSPECs (i.e., fine-granular TSPECs) are available for the users. In the rest of the simulations, multiple TSPECs are assumed to be available for the users.

Even though multiple TSPECs can enable the users to efficiently utilize the available network resources, the resource allocation based on the FCFS strategy depends largely on the order in which the users join the coalition, as discussed before. Hence, it neither guarantees the required minimum utility nor provides a fair TXOP allocation. The results for the allocated resources and the derived utility (i.e., quality in PSNR) given specific orderings in which the users join the coalition are shown in Table II. In Table II, Order 1, 2, and 3 represent illustrative orderings of joining the coalition, which are (1 2 3 4 5 6), (3 4 5 1 2 6), and (6 5 4 2 1 3), respectively.

### *C. Comparison of Channel Sharing Strategies*

In this section, we compare the discussed channel sharing strategies in terms of the derived utility as well as the AUD performance.

Simulation results in Table III show the individual utility and the AUD performance derived using the utility-based channel sharing strategies. We consider five multimedia users (User 1 to User 5) transmitting the same sequences as in Section VII-B with the maximum supported utility $\mathbf{U}^M = (U_1^M, \ldots, U_5^M) = (42\,\mathrm{dB}, 41\,\mathrm{dB}, 41\,\mathrm{dB}, 41\,\mathrm{dB}, 41\,\mathrm{dB})$ and minimum required

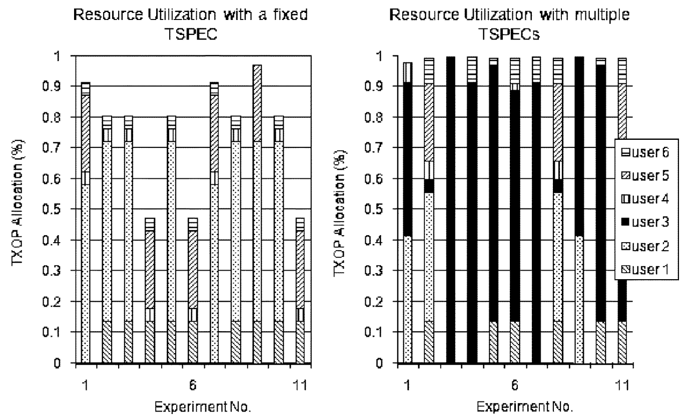



Fig. 2. Resource utilizations based on the FCFS channel sharing strategy (left) with a fixed TSPEC and (right) with multiple TSPECs. The resource utilizations are 72.5% and 99.4% on average, respectively. Note that user 3 cannot transmit its data in the left scenario.

TABLE II
RESOURCE UTILIZATION AND ACHIEVED UTILITY BASED ON FCFS

| Joining Order | Allocated TXOPs [%] [User 1, ..., User 6] | Individual PSNR [dB] [User 1, ..., User 6] |
|---|---|---|
| Order 1 | [11.1 29.2 58.3 0.0 0.0 0.0] | [37.0 38.0 36.3 − − −] |
| Order 2 | [0.0 0.0 89.6 8.3 0.0 0.0] | [− − 40.0 39.0 − −] |
| Order 3 | [11.1 29.2 8.3 8.3 33.3 8.3] | [37.0 38.0 26.4 39.0 40.0 38.0] |

TABLE III
ACHIEVED INDIVIDUAL UTILITY, AUD, AND $V(\hat{\mathbf{I}}_{C_j})$

| | FCFS (Average) | Shapley Value | KSBS |
|---|---|---|---|
| User 1 | 20.9 dB | 42.0 dB | 40.0 dB |
| User 2 | 30.6 dB | 27.0 dB | 38.8 dB |
| User 3 | 20.2 dB | 41.0 dB | 39.1 dB |
| User 4 | 20.5 dB | 41.0 dB | 39.3 dB |
| User 5 | 24.3 dB | 28.3 dB | 39.0 dB |
| AUD | 16.1031 | 5.5991 | 0.1820 |
| $V(\hat{\mathbf{I}}_{C_j})$ | -16.1031 | -5.5991 | -0.1820 |

utility set to 27 dB for all the users. We assume that the users experience different but fixed channel conditions. TSPECs are generated so that they can support 50 kbps rate intervals. The results based on the FCFS strategy are averaged across 100 experiments, as the resource allocation depends on the order in which the users join the coalitions. The channel sharing strategy based on the Shapley value considers the minimum required utility (i.e., considering only the feasible orderings).

We can easily observe that the FCFS strategy does not guarantee the minimum required utility. However, the channel sharing strategies based on the Shapley value considering the minimum utility requirements and the KSBS can explicitly ensure the minimum required utility. However, the AUD performance of the KSBS is better (i.e., smaller AUD) than that of the Shapley value because the KSBS can utilize the available resources more efficiently and the utility derived by the resource allocation based on the KSBS is closer to the reference utility.

Moreover, we can quantitatively evaluate the value of information in the simulation results. Given $V(\hat{\mathbf{I}}_{C_j})$ in Table III, which are obtained by the AUDs, the value of information can be calculated based on the definition in (12). For example, the value of $I = \{U_l(g_l(\psi_l))|l \in C_j\}$ can be computed as

$$\Delta V_I(\mathbf{I}_{C_j}^{FCFS}) = V(\mathbf{I}_{C_j}^{FCFS} \cup I) - V(\mathbf{I}_{C_j}^{FCFS}) = V(\mathbf{I}_{C_j}^{SV}) - V(\mathbf{I}_{C_j}^{FCFS}) = 10.5041$$

which means that the information $I$ can improve the AUD performance by approximately 10.5 dB in this illustrative simulation setting. Similarly, the value of other information can also be found (e.g., $\Delta V_I(\mathbf{I}_{C_j}^{FCFS}) = 16.0211$ for $I = \{U_l(g_l(\psi_l)), U_l^m|l \in C_j, \psi_l \in \Psi_l\}$). We determine that the AUD performance improves if more information is used and appropriate channel sharing strategies are deployed. But, this also leads to higher computational complexity, as discussed in the next section.

### D. Negotiating the Resource Sharing Strategies

In this section, we consider the decentralized negotiation on channel sharing strategies between a user and a coalition, and implement the algorithm discussed in Section III.

We assume that the users have a limited available time for negotiation, $T_k^A$, i.e., the patience factor $\delta_k^{t(r)}$ can be considered as $\delta_k^{t(r)} = \begin{cases} 1, & \text{if } t(r) \le T_k^A \\ 0, & \text{otherwise} \end{cases}$, for a user $k$. As discussed, a channel sharing strategy can be determined based on the coalition value as well as the achieved utility of the users. We assume that all the video sequences are encoded with different spatio-temporal resolutions. We also assume that a service interval $t_{SI}$ is divided into a fixed number of TXOPs (in our simulation one TXOP is 20% of $t_{SI}$) and deployed channel sharing strategies determine the number of allocated TXOPs for each users. Note that the number of TXOPs within a $t_{SI}$ affects the complexity for channel sharing strategies. For example, a larger number of TXOPs in a $t_{SI}$ (i.e., more refined TXOPs) can lead to more refined feasible utility set in the KSBS strategy. The simulation results are shown in Fig. 3.

The simulation results show that the interactions between incoming multimedia users and a coalition. As shown in Fig. 3(a), the FCFS strategy can only support a small limited number of users as the available TXOPs are allocated to the users who join the coalition earlier. The KSBS channel sharing strategy provides the highest coalition value as more users join the coalition. However, as shown in Fig. 3(b), the number of operations required for computing resource allocation increases exponentially with the number of users. Hence, the user who joins the coalition at round 7 and the coalition cannot agree on deploying the KSBS as their channel sharing strategy, since the available time for negotiation expires. Instead, they can agree on the channel sharing strategy based on the Shapley value or the FCFS. Note that the coalition value based on the Shapley value decreases as the coalition becomes congested. It is because the channel sharing strategy based on the Shapley value cannot efficiently utilize the available TXOPs, as discussed in Section IV. Therefore, we can conclude that if the coalition is not congested, the incoming users and coalitions can agree on the KSBS channel sharing strategy. However, as the coalition becomes congested, the users and coalitions need to take into account the available time for the negotiation. Note that the increased computational complexity incurred when the number of users becomes large can be significantly reduced simply by considering them as classes of users having similar multimedia requirements, as already discussed in Section IV.

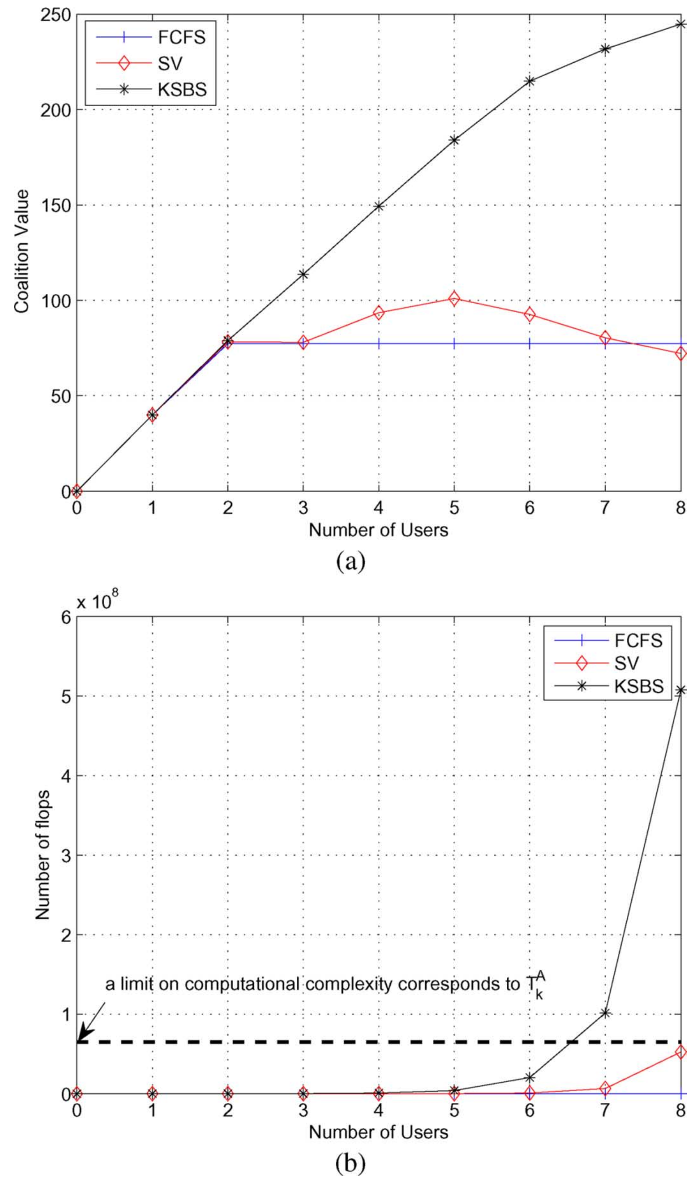
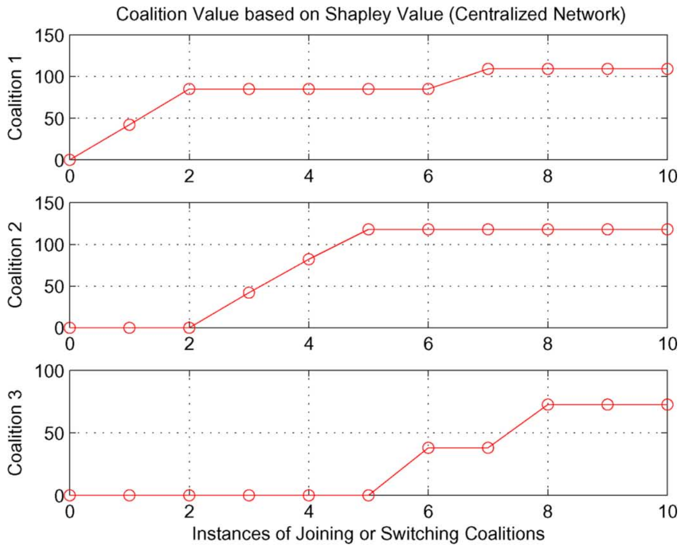



Fig. 3. (a) Coalition values and (b) required flops for computing resource allocation based on different channel sharing strategies.

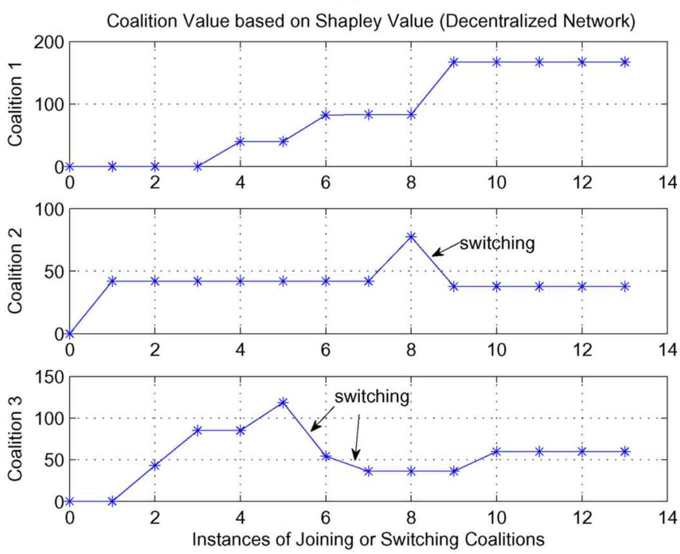
### E. System Dynamics Based on Incoming Order Independent Channel Sharing Strategies

In this section, we investigate the system dynamics in centralized and decentralized networks, where the deployed channel sharing strategies are based on the Shapley value, which does not consider the minimum required utility, and the KSBS.

We assume that there are three available channels ($\boldsymbol{\theta} = \{1, 2, 3\}$) and ten multimedia users can access the available channels. The users transmit different types of video sequences. We assume that the users experience different but fixed channel conditions. To illustrate the interactions of users,




(a)




(b)

Fig. 4. Coalition values derived based on the Shapley value in (a) centralized network and (b) decentralized network.

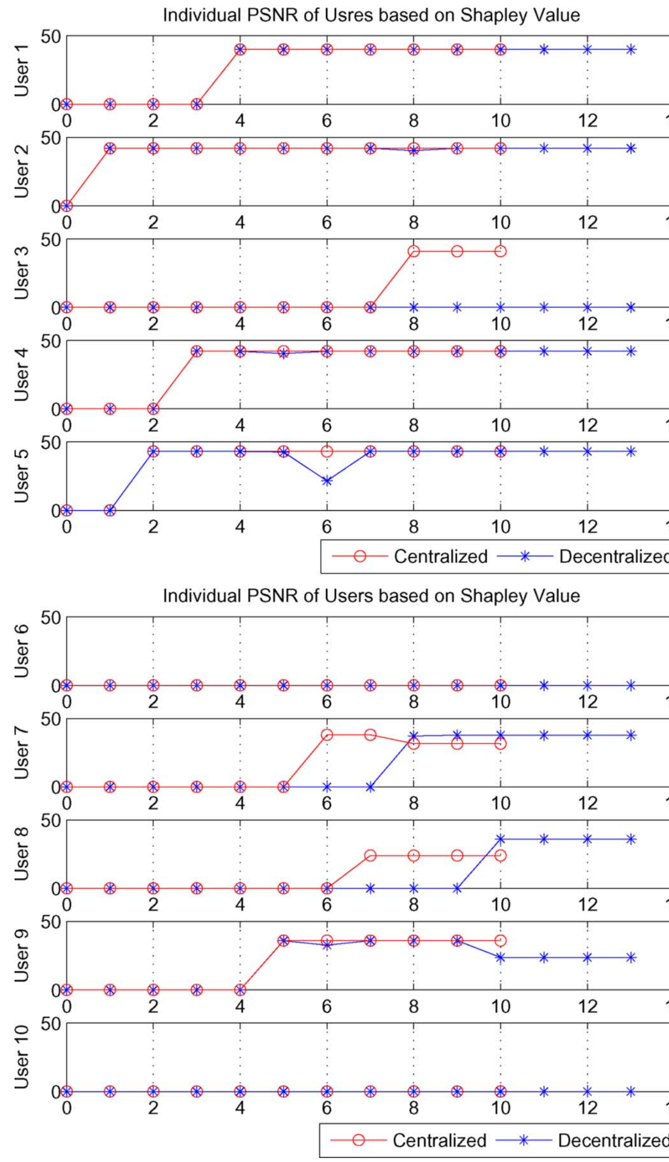



Fig. 5. Individual utility derived by the Shapley value in both networks.

we assume that incoming users join coalitions after existing users switch coalitions. In these simulations, the order in which the users join the network is set to be (2, 5, 4, 1, 9, 7, 8, 3, 6, 10) with low bandwidth required video sequences (from User 1 to User 5) and intensive bandwidth video sequences (from User 6 to User 10). The users can switch coalitions if they can improve their utility (in the decentralized network) or if they can improve both their utility and the system utility (in the centralized network). We assume that the induced overhead by switching coalitions is negligible, i.e., the switching threshold $U_k^{th} = 0$ for user $k$, $1 \leq k \leq 10$. Simulation results for the coalition value and the individual utility derived based on the Shapley value in centralized and decentralized networks are shown in Figs. 4 and 5, respectively.

Since the centralized network deploys the admission control policy, users' behavior that improves the system utility is allowed. Hence, the coalition value and the derived utility of users are aligned, i.e., utility improvement for each user implies utility improvement for the system. Hence, it is observed that the coalition value always increases as more users join or switch coalitions in the centralized network, while the coalition value can decrease when the users join or switch the coalitions in the decentralized network. For example, in the decentralized network, two users (User 5 and User 9) switch from coalition 3 to coalition 1 and one user (User 7) switches from coalition 2 to coalition 1. Even though they improve their individual utilities by switching coalitions, the system utility can decrease. Note that since the channel sharing strategy based on the Shapley value does not consider the minimum required utility, the minimum required utilities for several users in the system, such as User 8 in the centralized network and User 9 in the decentralized network, are not satisfied. In addition, due to the admission control policy deployed in the centralized network, users have a smaller chance of switching coalitions. Thus, the users in the centralized

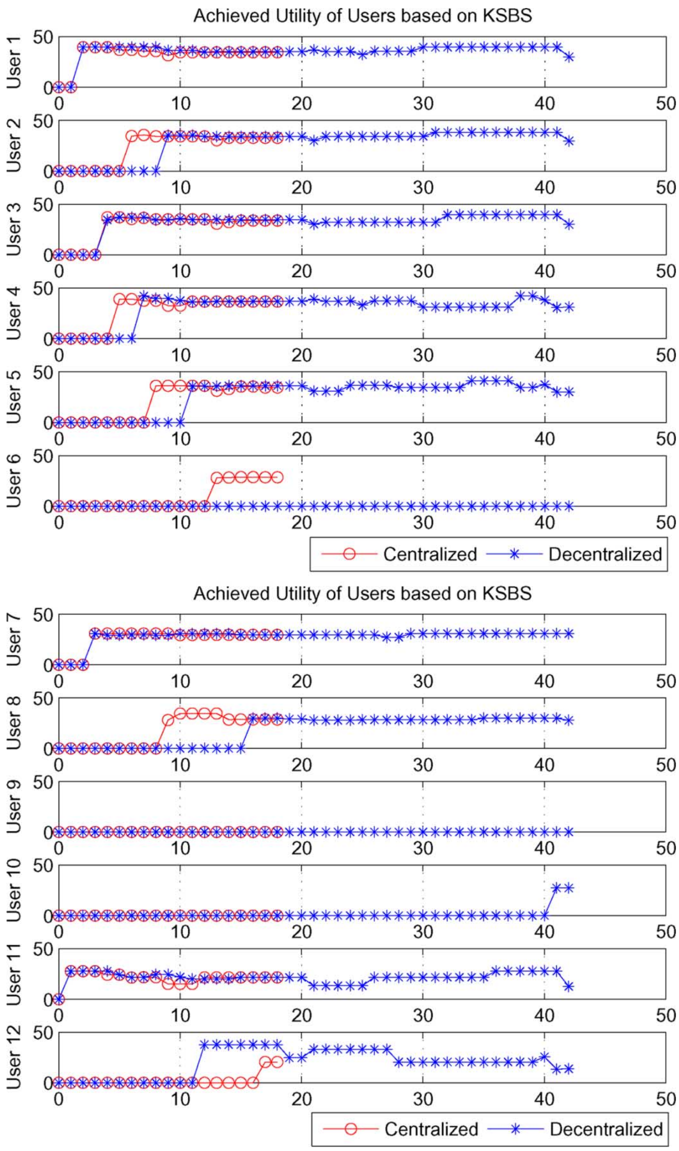



Fig. 6. Individual utility achieved by the KSBS in both networks. User 11 and User 12 transmit non-multimedia data.

network converge to a stationary distribution across the channels faster than the decentralized network.

Similar results for the channel sharing strategy based on the KSBS are shown in Fig. 6. As the channels can be shared by heterogeneous applications, we assume that there are multimedia users (User 1 to User 10) as well additional non-multimedia users (User 11 and User 12), which transmit general data in the system. Since the utility for the non-multimedia users can be increased as more rate is allocated, the utility for the non-multimedia users are modeled as a linear function to the allocated rates. We assume that the minimum required utility for the non-multimedia users is less than that of the video users.

Unlike the channel negotiation based on the Shapley value, which does not guarantee a minimum required utility for users, Fig. 6 shows that the KSBS-based channel negotiation can ensure the minimum required utility of the users in the system. Moreover, since the minimum required utility for the non-multimedia users is much less than the multimedia users, the non-multimedia users have the flexibility to switch between more coalitions. Consequently, the users tend to switch more frequently, which leads to the other users switching coalitions as well. Therefore, the number of instances required for the users to finish joining or switching coalitions is significantly larger if non-multimedia users are considered (see Figs. 5 and 6).

## VIII. Conclusion

In this paper, we propose an informationally decentralized framework for resource negotiation, where multimedia users exchange information about their requirements, and based on this, self-organize into coalitions which share the same channels. We focus on the information exchanged among the users and quantify the benefit of information exchanges in terms of AUD by introducing the value of information. By considering the difference between the AUDs obtained by different information exchanges, we can analytically quantify the benefit from exchanging additional information. In our simulation results, we quantitatively compare the proposed resource negotiation strategies in terms of the value of information as well as the required complexity. An important topic of future research is the applications of the proposed decentralized resource negotiation framework in emerging cognitive radio networks, Bluetooth piconets, peer-to-peer networks, etc. The various communication overheads and complexities associated with implementing the proposed solutions in the distributed network can be exactly quantified for a specific implementation. Then, a suitable solution can be selected based on the tradeoffs among the proposed methods.

## Appendix

We show that the utility-based Shapley value is not guaranteed to utilize all the available TXOPs in coalition $C_j$. Suppose that $\Pi = \{\pi_1, \ldots, \pi_{m!}\}$ is the set of all permutations on coalition $C_j$ with $m$ users. The achieved utility for permutation $\pi_i$ can be expressed as

$$\mathbf{U}(\pi_i) = \left(U_1(R_{j1}^M \cdot \tau_1^{(i)}), \ldots, U_m(R_{jm}^M \cdot \tau_m^{(i)})\right) \tag{21}$$

where $\sum_{l=1}^{m} \tau_l^{(i)} = 1$ for all $1 \leq i \leq m!$. Note that $U_l(R_{jl}^M \cdot \tau_l^{(i)})$ is the resulting utility for the allocated TXOP $\tau_l^{(i)}$ and is the marginal contribution of user $l$ to the coalition value with respect to $\pi_i$ since the FCFS policy is deployed. Let the achieved utility based on the Shapley value be $\mathbf{U}_{SV}$, which can be expressed as

$$\mathbf{U}_{SV} = \left(U_1(R_{j1}^M \cdot \tau_1^{(SV)}), \ldots, U_m(R_{jm}^M \cdot \tau_m^{(SV)})\right)$$

where $(\tau_1^{(SV)}, \ldots, \tau_m^{(SV)})$ denotes the allocated TXOPs based on the Shapley value. Based on the definition of Shapley value, $\mathbf{U}_{SV}$ can be represented using (21) as

$$\mathbf{U}_{SV} = \left(\frac{1}{m!}\sum_{i=1}^{m!} U_1(R_{j1}^M \tau_1^{(i)}), \ldots, \frac{1}{m!}\sum_{i=1}^{m!} U_m(R_{jm}^M \tau_m^{(i)})\right).$$

Since $U_j$ is a non-decreasing and concave function, by the Jensen's inequality, we have

$$U_l(R_{jl}^M \tau_l^{(SV)}) = \frac{1}{m!} \sum_{i=1}^{m!} U_l(R_{jl}^M \tau_l^{(i)}) \leq U_l \left( \frac{1}{m!} \sum_{i=1}^{m!} R_{jl}^M \tau_l^{(i)} \right)$$

which leads to $\tau_l^{(SV)} \leq (1/m!) \sum_{i=1}^{m!} \tau_l^{(i)}$. Therefore

$$\sum_{l=1}^{m} \tau_l^{(SV)} \leq \sum_{l=1}^{m} \frac{1}{m!} \sum_{i=1}^{m!} \tau_l^{(i)} = \frac{1}{m!} \sum_{i=1}^{m!} \sum_{l=1}^{m} \tau_l^{(i)} = 1.$$

The equality holds if $U_j$ is a linear function. Therefore, the utility-based Shapley value does not guarantee the complete utilization of available TXOPs.

## REFERENCES


[1] T.-J. Lee and G. De Veciana, "A decentralized framework to achieve max-min fair bandwidth allocation for ATM networks," in *Proc. IEEE Global Telecommu. Conf 1998. (GLOBECOM 98)*, Nov. 1998, vol. 3, pp. 1515–1520.

[2] J. G. Kim and M. M. Krunz, "Bandwidth allocation in wireless networks with guaranteed packet-loss performance," *IEEE/ACM Trans. Netw.*, vol. 8, pp. 337–349, Jun. 2000.

[3] S.-T. Sheu and T.-F. Sheu, "A bandwidth allocation/sharing/extension protocol for multimedia over IEEE 802.11 ad hoc wireless LANs," *IEEE J. Select. Areas Commun.*, vol. 19, pp. 2065–2080, Oct. 2001.

[4] C. Raman, R. Yates, and N. Mandayam, "Scheduling variable rate links via a spectrum server," in *Proc. 1st IEEE Int. Symp. New Frontiers in Dynamic Spectrum Access Netw. (DySPAN 2005)*, Nov. 8–11, 2005, pp. 110–118.

[5] H. Zheng and L. Cao, "Device-centric spectrum management," in *Proc. 1st IEEE Int. Symp. New Frontiers in Dynamic Spectrum Access Netw. (DySPAN 2005)*, Nov. 8–11, 2005, pp. 56–65.

[6] J. Zhao, H. Zheng, and G.-H. Yang, "Distributed coordination in dynamic spectrum allocation networks," in *Proc. 1st IEEE Int. Symp. New Frontiers in Dynamic Spectrum Access Netw. (DySPAN 2005)*, Nov. 8–11, 2005, pp. 259–268.

[7] M. E. Gaston and M. desJardins, "Agent-organized networks for dynamic team formation," in *Proc. Int. Joint Conf. Autonomous Agents and Multiagent Systems (AAMAS '05)*, 2005, pp. 230–237.

[8] L. Barton and V. H. Allan, "Methods for coalition formation in adaptation-based social networks," *Lecture Notes in Computer Science (LNCS)*, vol. 4676/2007, pp. 285–297, 2007.

[9] S. Kraus, O. Shehory, and G. Taase, "The advantages of compromising in coalition formation with incomplete information," in *Proc. Int. Joint Conf. Autonomous Agents and Multiagent Systems (AAMAS '04)*, Jul. 2004, pp. 588–595.

[10] G. Chalkiadakis and C. Boutilier, "Bayesian reinforcement learning for coalition formation under uncertainty," in *Proc. Int. Joint Conf. Autonomous Agents and Multiagent Systems (AAMAS '04)*, Jul. 2004, pp. 1088–1095.

[11] O. Shehory and S. Kraus, "Feasible formation of coalitions among autonomous agents in nonsuperadditive environments," *Comput. Intell.*, vol. 15, no. 3, pp. 218–251, Aug. 1999.

[12] O. Shehory and S. Kraus, "Methods for task allocation via agent coalition formation," *Artif. Intell.*, vol. 101, pp. 165–200, May 1998.

[13] E. A. Billard and J. C. Pasquale, "Effects of delayed communication in dynamic group formation," *IEEE Trans. Syst., Man, Cybern.*, vol. 23, pp. 1265–1275, Sep. 1993.

[14] M. J. Osborne and A. Rubinstein, *A Course in Game Theory*. Cambridge, MA: The MIT Press, 1994.

[15] A. S. Nowak and T. Radzik, "The Shapley value for n-person games in generalized characteristic function form," *Games Econ. Beh.*, vol. 6, pp. 150–161, 1994.

[16] E. Winter, "The Shapley value," in *Handbook of Game Theory with Economic Applications*, R. Aumann and S. Hart, Eds. NewYork: Elsevier, 2002, vol. 3, ch. 53, pp. 2025–2054.

[17] Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification: Medium Access Control (MAC) Enhancements for Quality of Service (QoS) Enhancements, 2005, IEEE Std 802.11e-2005.

[18] M. van der Schaar and P. A. Chou, *Multimedia Over IP and Wireless Networks: Compression, Networking, and Systems*. New York: Academic, 2007.

[19] H. Garcia-Molina, "Elections in a distributed computer system," *IEEE Trans. Comput.*, vol. 1, no. 1, pp. 48–59, Jan. 1982.

[20] S. Singh and J. Kurose, "Electing leaders based upon performance: The delay model," in *Proc. Int. Conf. Distributed Computer Systems*, May 1991, pp. 464–471.

[21] H. Hill and R. Kung, "A Diff-Serv enhanced admission control scheme," in *Proc. IEEE Global Telecommu. Conf. 2001 (GLOBECOM '01)*, Nov. 2001, vol. 4, pp. 2549–2555.

[22] S. Boyd and L. Vandenberghe, *Convex Optimization*. New York: Cambridge Univ. Press, 2004.

[23] L. S. Shapley, "A value for n-person games," in *Contributions to the Theory of Games II (Annals of Mathematics Studies 28)*, H. W. Kuhn and A. W. Tucker, Eds. Princeton, NJ: Princeton Univ. Press, 1953, pp. 307–317.

[24] D. Monderer and D. Samet, "Variations on the Shapley value," in *Handbook of Game Theory with Economic Applications*, R. Aumann and S. Hart, Eds. New York: Elsevier, 2002, vol. 3, ch. 54, pp. 2055–2076.

[25] H. Park and M. van der Schaar, "Bargaining strategies for networked multimedia resource management," *IEEE Trans. Signal Process.*, vol. 55, no. 7, pp. 3496–3511, Jul. 2007.

[26] Digital Video Compression, AXIS Communications, 2004, White Paper.

[27] E. Kalai and M. Smorodinsky, "Other solutions to Nash's bargaining problem," *Econometrica*, vol. 43, pp. 513–518, 1975.

[28] D. Monderer and L. S. Shapley, "Potential games," *Games Econ. Beh.*, vol. 14, no. 44, pp. 124–143, 1996.



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