INFORMATION-DRIVEN RESOURCE NEGOTIATION STRATEGIES FOR MULTIMEDIA APPLICATIONS

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ABSTRACT

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 discuss various network 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. To quantify the utility benefit derived by exchanging different information, we define a new metric referred to as the value of information. Simulation results show the improvements that can be achieved when various information is exchanged between users, and discuss the required complexity involved in implementing the various resource negotiation strategies.

Index Terms— Multi-user multimedia resource management, value of information, coalition game.

1. INTRODUCTION

Several multimedia applications such as multimedia streaming services, video conferencing, 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 requirements. Hence, developing efficient and fair network resource negotiation strategies for multimedia users is a challenging task.

Various resource negotiation strategies for multi-user have been proposed for wired or wireless networks, including recently cognitive radio networks (see e.g., [1–3]). While some strategies have been designed for centralized networks, where a central resource coordinator optimizes and distributes the network resources, decentralized approaches for the network resource negotiation strategies are also proposed to provide improved scalability as the number of users in the network increases (e.g., decentralized spectrum sharing policy [3]). While previously proposed decentralized strategies enable the users to share the available network resources in decentralized manners, they cannot be adapted for multimedia users, who have different information availability and requirements, as the strategies are developed based on pre-determined fairness rules and pre-determined information exchanges.

In this paper, we propose decentralized solutions for network resource negotiation strategies, where multiple users self-organize into coalitions which share the same network resources and can negotiate the network resource division based on information exchanges about their QoS (Quality of Service) requirements. To model the resource division among the users in coalitions, we adopt coalition (cooperative) game theory [4], which focuses on the division of the coalition value (e.g., aggregated utility) based on fairness axioms [5]. Note that coalition game concepts are relevant in situations where a scarce (network) resource needs to be rationed fairly among competing claimants.

We focus on the impact of different types of information exchanges on the derived utility, because different types of information exchanges can lead to the deployment of distinct network resource negotiation strategies. For illustration, in this paper we consider several network resource negotiation strategies, such as FCFS (First come, first served) policies, and more advanced policies motivated by game theoretic concepts of the Shapley value and axiomatic bargaining solutions [4]. We discuss the information that needs to be exchanged among users to implement these strategies, and compare its impact on utility as well as the computational complexity. For this, the value of information exchanges is defined as a metric to explicitly measure how much the users can benefit from exchanging the information.

This paper is organized as follows. Section 2 describes the considered network configurations and information exchanges. In Section 3, various network resource negotiation strategies are discussed and value of information is defined as a performance measure. Simulation results are presented in Section 4 and the conclusions are drawn in Section 5.

2. DECENTRALIZED RESOURCE NEGOTIATION

2.1. Decentralized Network Resource Negotiation

To illustrate our proposed framework, we model network resources as being divided into multiple frequency bands (or channels) that are accessible to users. We assume that the network resources (i.e., channels) can be divided using time division multiple access (TDMA), since this solution has often been deployed in IEEE 802.11 standards such as IEEE 802.11e HCF (Hybrid Coordinator Function) [6]. Users sharing the same channel negotiate their *transmission opportunities* (TXOPs) $\tau_{j_k k}$, which represent a *fraction* of the service interval (t_{SI}) allocated to user k in channel j_k. An illustrative example of the negotiation on TXOP division in channel j for IEEE 802.11e wireless LAN [6] is shown in Fig. 1.

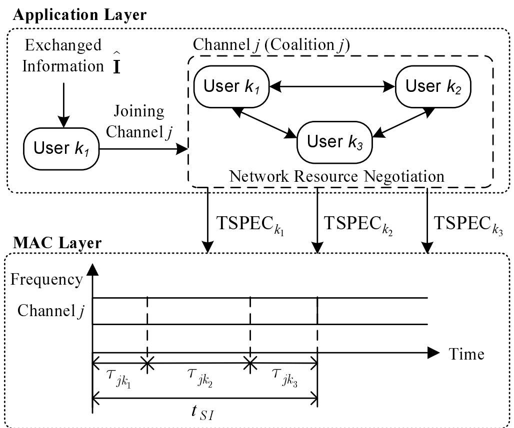

Fig. 1. An illustration for a decentralized TXOP negotiation.

2.2. Information Exchanges

There are N channels, $\boldsymbol{\theta} = \{1, \ldots, N\}$, and a user k can access the channels $\boldsymbol{\theta}_k \subseteq \boldsymbol{\theta}$. The experienced channel condition[1] for a user is used to determine its maximum rates that can be achieved in the channels. The set of maximum achievable rates R_{jk}^{MAX} for user k in channels $j \in \boldsymbol{\theta}_k$ is expressed as $\mathbf{R}_k^{MAX}(\boldsymbol{\theta}_k) = \{R_{jk}^{MAX} | j \in \boldsymbol{\theta}_k\}$. Moreover, the information about multimedia users can be conveyed using traffic specification (TSPEC) techniques, which are used in IEEE 802.11e [6] for negotiating TXOP division. The set of available multiple TSPECs for user k is denoted by $\Psi_k = \{\psi_k^{h_k} | 1 \le h_k \le H_k\}$, where a TSPEC $\psi_k^{h_k} \in \Psi_k$ can be used to determine the effective rate $g_k(\psi_k^{h_k})$ [6]. In addition, the achievable utility $U_k(g_k(\psi_k^{h_k}))$ and the minimum required utility U_k^{min} can be included in the information about TSPECs. The utility is represented by a quality measure, Peak Signal-to-Noise Ratio (PSNR). Therefore, the set of information about user k can be expressed as $\mathbf{I}_k = \{\boldsymbol{\theta}_k, \mathbf{R}_k^{MAX}(\boldsymbol{\theta}_k), \mathbf{I}_{TSPEC_k}\}$, where the information about TSPEC is $\mathbf{I}_{TSPEC_k} = \{(\psi_k^{h_k}, U_k(g_k(\psi_k^{h_k})), U_k^{min}) | \psi_k^{h_k} \in \Psi_k\}$.

2.3. Utility-based Network Resource Negotiation

A channel sharing strategy $\mathcal{G} \in \boldsymbol{\mathcal{G}}$ can be designed for allocating TXOPs and explicitly considering the utility impact of the allocated TXOPs on multimedia users. A utility-based channel sharing strategy $\mathcal{G}$ in coalition C_j with m_j users is defined as

$$\mathcal{G}(v(C_j)) = \left([\mathcal{G}(v(C_j))]_1, \ldots, [\mathcal{G}(v(C_j))]_{m_j} \right), \quad (1)$$

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

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, which can be converted to the TXOPs τ_{jk}, considering the utility impact.

As various utility-based channel sharing strategies require different types of information exchanges, we discuss several strategies, and analyze the information exchanges and computational complexity required for implementing the strategies in the next section.

3. INFORMATION-DRIVEN RESOURCE NEGOTIATION STRATEGIES

3.1. FCFS Channel Sharing Strategy

The channels can be shared based on a FCFS strategy, which is often used in practice [6, 7]. This strategy requires the information about the maximum achievable rates in channels and the rate requirements of users. Hence, the necessary information is given by $\mathbf{I}_{C_j}^{FCFS} \triangleq \{R_{jl}^{MAX}, \mathbf{I}_{TSPEC_l}^{FCFS} | l \in C_j\}$, where $\mathbf{I}_{TSPEC_l}^{FCFS} \triangleq \{\psi_l^{h_l} | \psi_l^{h_l} \in \Psi_l\}$ which specifies the rate requirements. Then, user k can compute the rates achieved by joining coalition C_j, which is expressed as

$$(1 - \textstyle\sum_{l \in C_j} \tau_{jl}) \cdot R_{jk}^{MAX}, \quad (2)$$

where $\tau_{jl} = g_l(\psi_l)/R_{jl}^{MAX}$ denotes the allocated TXOP to user l deploying TSPEC ψ_l in C_j. Hence, the maximum utility that user k can derive is determined by deploying a TSPEC $\psi_k^{h_k^j} \in \Psi_k$ that corresponds to the highest effective rate $g_k(\psi_k^{h_k^j}) \le (1 - \sum_{l \in C_j} \tau_{jl}) R_{jk}^{MAX}$. Eq. (2) shows that the computational complexity required to compute the resource allocation can be estimated by $O(m_j)$ flops (floating point operations), which is linearly increasing with the number of users in the coalitions. Note that the derived utility based on the FCFS strategy can be viewed as the *marginal contribution*[2] of user k to C_j, since $U_k(g_k(\psi_k^{h_k^j})) = \Delta v_k(C_j) = \sum_{l \in C_j \cup \{k\}} U_l(g_l(\psi_l^{h_l^j})) - \sum_{l \in C_j} U_l(g_l(\psi_l^{h_l^j}))$.

Although the FCFS strategy can consider the impact on utility with a lower complexity, the resource allocation 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.

3.2. Utility-based Channel Sharing Strategies

3.2.1. Incoming Order Independent Strategy

For the users having equal rights to access the network resources, the TXOP can be allocated based on their average marginal contributions to the coalition value. To determine

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

the coalition value, the users must exchange information about their achievable utilities. Hence, the necessary information for user k is given by $\mathbf{I}_{C_j}^{SV} \triangleq \{R_{jl}^{MAX}, \mathbf{I}_{TSPEC_l}^{SV} | l \in C_j\}$, where $\mathbf{I}_{TSPEC_l}^{SV} \triangleq \{(\psi_l^{h_l}, U_l(g_l(\psi_l^{h_l}))) | \psi_l^{h_l} \in \Psi_l\}$. Based on $\mathbf{I}_{C_j}^{SV}$, user k can compute the resource allocation, such that the users in C_j can derive the utility corresponding to their *averaged marginal contributions*, i.e.,

$$U_l(g_l(\psi_l^{h_l})) = \{\frac{1}{|\Pi(C_j \cup \{k\})|!} \sum_{\check{C} \in \Pi(C_j \cup \{k\})} \Delta v_l(\check{C})\} \quad (3)$$

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 [4, 5]. The complexity for computing (3) is $O(m_j!)$ flops, which increases factorially with respect to the number of users. Due to the high complexity, deploying this strategy becomes impractical when there are many users. However, the number of users can be limited to a reasonably small number, as the users can leave or switch coalitions if they become congested.

Note that (3) includes *infeasible* orderings, where some users' minimum required utilities are not satisfied, leading to inefficient network resource utilization. The information about the minimum required utility can guarantee a minimum required utility for multimedia users, which will be discussed in the next section.

3.2.2. Channel Sharing Strategy with Minimum Utility Requirements

For multimedia users, ensuring a minimum required utility is important. Hence, users can negotiate the TXOP division by exchanging the information about their minimum required utilities while satisfying the minimum required utility. Hence, the information $\mathbf{I}_{C_j}^{BS} \triangleq \{R_{jl}^{MAX}, \mathbf{I}_{TSPEC_l}^{BS} | l \in C_j\}$, where $\mathbf{I}_{TSPEC_l}^{BS} \triangleq \{(\psi_l^{h_l}, U_l(\psi_l^{h_l}), U_l^{min}) | \psi_l^{h_l} \in \Psi_l\}$, needs to be exchanged.

The channel sharing strategy based on the Shapley value discussed in Section 3.2.1 can be improved by considering only *feasible* orderings, where the utility achieved by all users satisfies the users' minimum required utility. Hence, the utility that user k can derive is computed based on (3) replaced by $\Pi^*(C_j \cup \{k\})$ instead of $\Pi(C_j \cup \{k\})$, 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, the users can negotiate TXOP division based on their average marginal contributions and can explicitly ensure the minimum required utility. However, because this channel sharing strategy is not guaranteed to utilize all TXOPs, it becomes an inefficient channel sharing strategy.

Alternatively, user k can allocate the resources 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. The solutions that satisfy these properties are the is the *axiomatic bargaining solution* [4]. The axiomatic bargaining solution ϕ is given by

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

where $\mathbf{S}_j$ and $\mathbf{d}_j$ denote the feasible utility set formed by all sets of feasible TXOP divisions and the set of minimum required utilities in $C_j \cup \{k\}$, respectively. $\phi_l(\mathbf{S}_j, \mathbf{d}_j)$ denotes the derived utility for user l, i.e., $U_l(g_l(\psi_l^{h_l})) = \phi_l(\mathbf{S}_j, \mathbf{d}_j)$. More details for the axiomatic bargaining solutions can be found in our previous work [4].

The computational complexity for these axiomatic bargaining solutions is dominated by identifying the complete feasible utility set $\mathbf{S}_j$ for $j \in \boldsymbol{\theta}_k$. For quantized service intervals with the step size $\Delta t\,(\leq t_{SI})$, the computational complexity required for identifying $\mathbf{S}_j$ can be estimated as $O\left((t_{SI}/\Delta t)^{m_j}\right)$ flops, which increases exponentially.

In this paper, we consider the Kalai-Smorodinsky bargaining solution (KSBS), which proportionally divides the resources to each user's maximum achievable utility [8], as an illustrative example.

3.3. Performance Measures

To quantify the performance of the considered channel sharing strategies, we define 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 determined based on the KSBS with the finest-granularity TSPECs (i.e., $\psi_k^{h_k}$ with large H_k), and all the information required for the network resource negotiation in this paper. The AUD is defined as

$$AUD_j \triangleq \frac{1}{m_j} \sum\nolimits_{l=1}^{m_j} |U_{jl}^R - U_l(g_l(\psi_l^{h_l^j}))|, \quad (4)$$

where $\mathbf{U}_j^R = (U_{j1}^R, \ldots, U_{jm_j}^R)$ denotes a reference utility.

Note that the AUD decreases as the utility achieved by a deployed strategy approaches the reference utility. The impact of the additional information exchanges on the AUD is quantified by the value of information, which represents the distance between the utility achieved based on the exchanged information and the reference utility. Thus, the value of information of I with respect to information $\hat{\mathbf{I}}$ is defined as

$$\Delta V_I(\hat{\mathbf{I}}) = V(\hat{\mathbf{I}} \cup I) - V(\hat{\mathbf{I}}), \quad (5)$$

where $V(\hat{\mathbf{I}}_{C_j}) = -\min_{\mathcal{G}_j \in \hat{\boldsymbol{\mathcal{G}}}_j} \{AUD_j\}$ represents the minimum value of AUD given the exchanged information $\hat{\mathbf{I}}_{C_j}$ and $\mathcal{G}_j$ among the available channel sharing strategies $\hat{\boldsymbol{\mathcal{G}}}_j$. The value of information measures how much information I can move the derived utility $\mathbf{U}_j$ closer to the reference utility.

4. SIMULATION RESULTS

We assess the performance of the considered channel sharing strategies, where multiple multimedia users transmit their multimedia streams (e.g., video sequences). Multiple TSPECs

User	1	2	3	4	5	AUD
FCFS [dB]	20.9	30.6	20.2	20.5	24.3	16.1031
SV [dB]	42.0	27.0	41.0	41.0	28.3	5.5991
KSBS [dB]	40.0	38.8	39.1	39.3	39.0	0.1820

Table 1. Achieved Individual Utility and AUD

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 [6]. TSPECs are generated so that they can support 50kbps rate intervals. The video sequences are encoded at specific target rates using on the H.264/AVC based video encoder.

4.1. Comparison of Channel Sharing Strategies

Simulation results in Table 1 show the individual utility and the AUD performance derived using the utility-based channel sharing strategies. We consider five multimedia users (User 1 to 5) with the maximum supported utility $\mathbf{U}^{MAX}$ = (42dB, 41dB, 41dB, 41dB, 41dB) and minimum required utility set to 27dB for all the users. The results based on the FCFS strategy are averaged across 100 experiments. The strategy based on the Shapley value considers the minimum required utility (i.e., considering only the feasible orderings) as discussed in Section 3.2.2. The feasible utility set for the KSBS is identified as several utility points obtained by setting Δt = 50Kbps.

We can easily observe that the FCFS strategy does not guarantee the minimum required utility. However, the strategies based on the Shapley value 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.

Fig. 2 shows the obtained $V(\hat{\mathbf{I}}_{C_j})$, and the required computational complexity given different information exchanges $\hat{\mathbf{I}}_{C_j} \in \{\mathbf{I}_{C_j}^{FCFS}, \mathbf{I}_{C_j}^{SV}, \mathbf{I}_{C_j}^{BS}\}$. As discussed, higher computational complexity and more communication overhead (i.e., more information exchanges) are generally required to achieve a higher values of $V(\hat{\mathbf{I}}_{C_j})$. This implies that the achieved utility based on more information exchanges can approach the reference utility, while higher computational complexity is required.

5. CONCLUSION

In this paper, we propose an informationally decentralized framework for network 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, as the exchanged information induces the users to deploy distinct network resource negotiation strategies, thereby leading to different derived utilities as well as

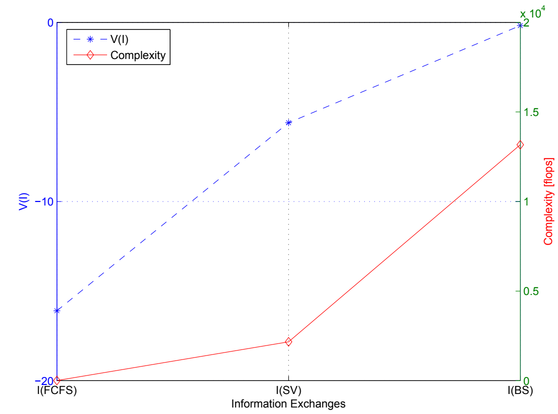

Fig. 2. $V(\hat{\mathbf{I}}_{C_j})$ and the corresponding required complexity.

different levels of computational complexity. We quantify the benefit of information exchanges by introducing the value of information. In our simulation results, we quantitatively compare the different channel sharing strategies and the value of information as well as the required complexity.

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