Quality-Based Resource Brokerage for Autonomous Networked Multimedia Applications

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***Abstract*—In this paper, we assume that the network resources are managed by several brokers, which are endowed with resources by a (remote) central resource manager according to several predetermined policies. Our focus is on autonomous multimedia users. We propose a novel resource management scheme, where resource brokers choose well-suited axiomatic bargaining solutions to divide their allocated resources among the users associated with them. These resource division solutions enable resource brokers to provide strict minimum video quality guarantees according to the (varying) number of multimedia users associated with them. Finally, we show that the proposed solution enables us to model the problem of selecting resource brokers by multimedia users as an unweighted congestion game, thereby ensuring convergence to a stationary distribution of users across resource brokers. We investigate the number of required users' switches to reach the stationary distribution, and quantify the fairness of the stationary distribution by introducing a novel quality fairness comparison metric for the users.**

***Index Terms*—Axiomatic bargaining solution, congestion games, multimedia resource management, quality-driven admission control, resource broker.**

I. Introduction

NUMEROUS multimedia applications are recently emerging and these applications are increasingly serviced over various resource constrained network infrastructures (e.g., wireless networks). However, developing efficient resource management strategies for multimedia users sharing the same network infrastructure is a challenging task, because multimedia users are assumed to be autonomous and care only about the utility benefits that they can derive from the network. Each user will try to acquire as much of the network resources as possible, unless a regulatory mechanism exists in the network. Thus, a regulatory central system is needed that can ensure fair and efficient allocation of resources. To model such networks, we use the concept of (intermediate) brokers, which has been successfully deployed in several applications [1]–[3]. We consider that the network resources are managed by several resource brokers (RBs). The RBs comply with the regulation policies imposed by a (remote) central resource manager (CRM), and the regulation policies determine how the network resources should be divided among several RBs (e.g., spectrum etiquette [4]). Examples of such networks include wireless LANs [5], dynamic spectrum agile wireless networks [1]–[3], etc.

A. Proposed Approach and Contributions

In this paper, we focus on how to design network resource brokerage solutions for multimedia applications (users). We assume that the users can transmit their multimedia bitstreams by associating themselves with any of the several RBs located in their proximity [6]. The motivation of using RBs is to provide an efficient, yet flexible resource management solution for distributing the resources of the CRM, by enabling RBs to design different resource division rules for their users. We assume that the multimedia users are autonomously selecting the RB that can provide them the highest minimum video quality for their transmission. The RBs are dividing their resources among the several autonomous multimedia users associated with them.

To explicitly consider the impact of allocated resources on the multimedia quality and ensure that the minimum required quality is guaranteed for all users joining their subnetworks, the RBs need to deploy quality-aware resource division policies. To enable this, we propose to deploy axiomatic bargaining solutions for the RBs [7]–[9]. We choose appropriate bargaining solutions that enable RBs to provide minimum video quality guarantees depending only on the (varying) number of multimedia users associated with them. In particular, the Kalai–Smorodinsky bargaining solution (KSBS) [8] and the egalitarian bargaining solution (EBS) [9] are deployed and designed to guarantee multimedia users a minimum quality level based on the number (and not the specific multimedia type) of users currently present in the network. After multimedia users join their subnetworks, the RBs use these bargaining solutions to divide the available resources based on the specific characteristics of the users associated with them. The resulting achievable quality for the users will exceed their minimum desired quality since otherwise the users would not have associated themselves with this RB. Note that in this paper, we focus on the admission control problem and we do

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not consider the real-time video transmission problem after a user associates itself with a RB, as this topic was extensively studied in prior work (see, e.g., [10] for a review).

Multimedia users also have a *desired* maximum quality. Hence, achieving a higher quality than this does not lead to an improved user satisfaction, and resources may be unnecessarily wasted if the desired maximum quality is not considered. The waste of resources degrades the network performance because, as it will be shown in the paper, it may lead to a lower number of admitted users in the network and a lower minimum quality guarantee that can be provided by RBs. Hence, this paper focuses on deploying KSBS and EBS as quality-aware resource division policies that explicitly consider the desired maximum quality of multimedia users and that enables RBs to advertise the minimum quality guarantees they can provide to the various users. Based on the advertised minimum quality guarantees, multimedia users autonomously select and switch RBs. The merit of the proposed approach is the extent of multimedia domain specific modeling in developing the game theoretic framework driving the design and implementation of the proposed resource brokerage solution. This is in contrast to much of the research in quality-based game theoretic methods for networks (see, e.g., [11] for a review), which do not consider multimedia characteristics and minimum requirements.

To investigate the behavior of the proposed system over time, we model the proposed admission control policy as a *quality-driven* unweighted congestion game [12]. The primary advantage for modeling the considered resource allocation scheme as an unweighted congestion game is that there exists at least one pure strategy Nash equilibrium (PSNE). This implies that the decentralized noncollaborative interaction of users trying to maximize their achievable quality does converge to a stationary distribution over the subnetworks without the specific control of a central authority. To quantify how fairly the resources are allocated by the proposed admission control solution at PSNE, we define the *fairness comparison metric* (FCM), which represents the deviation of the actual video quality benefit at PSNE as opposed to that obtained by the centralized fair solution (i.e., the smallest quality benefit deviation from the average of the actual quality benefit).

B. Related Works

The concept of (intermediate) brokers has been successfully deployed in several applications and protocols [1]–[3], [5]. While RBs have already been proposed to manage different type of resources [e.g., spectrum access, transmission opportunity (TXOP) [13], etc.], they did not explicitly consider how such network resource management should be implemented for multimedia users, which have different characteristics and constraints (e.g., they require a minimum video quality to be received). Our approach using the axiomatic bargaining solutions deployed in RBs can explicitly consider the impact of allocated resources on the multimedia quality and ensure that the minimum required quality is guaranteed for all users joining their subnetworks. Thus, the RBs can deploy quality-aware resource division policies.

Axiomatic bargaining theory was already used to fairly allocate resources for various networks [14], [15]. However, prior

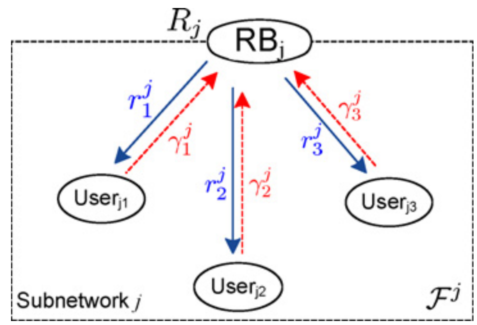


Fig. 1. Information exchanges and resource allocation among RBs and users.

research does not consider the resulting impact on the multimedia quality for various content-aware applications. Hence, these existing solutions are not suitable for our quality-based brokerage problem. While axiomatic bargaining solutions are deployed for resource allocation for multimedia users in [16], [17], the focus is on mathematically interpreting several well-known bargaining solutions such as Nash bargaining solution (NBS) [7] and KSBS for multimedia applications given a *fixed* number of users with *known* multimedia characteristics. However, in this paper, we focus on the admission control scheme that can be deployed by RBs, and not on designing fairness schedules for multimedia users. Our approach based on the KSBS and the EBS enables RBs to provide minimum video quality guarantees depending only on the *varying* number (and not the specific multimedia type) of multimedia users associated with them. Based on this, the admission control can be modeled as a quality-driven unweighted congestion game. While the congestion game has been successfully used in several applications such as routing and load balancing [18], [19], previous research focuses on distributing the available network resources without explicitly considering the impact on the multimedia quality derived by the users. Instead, in this paper, we are operating on the utility rather than on the resource domain, thereby being able to take into account the derived quality of multimedia users.

This paper is organized as follows. In Section II, we propose the brokerage-based resource management strategies. In Section III, we design quality-aware admission control schemes using axiomatic bargaining solutions. In Section IV, we model the proposed admission control scheme as a quality-driven unweighted congestion game. In Section V, we investigate the properties of the PSNE and define the FCM in terms of multimedia quality. Simulation results are provided in Section VI. The conclusions are drawn in Section VII.

II. Brokerage-Based Resource Management Strategies

In this section, we consider a brokerage-based decentralized admission control mechanism that provides scalable and flexible resource allocation based on different quality-driven resource division policies.

A. Description of Brokerage-Based System

The considered brokerage-based system consists of a hierarchical structure of the CRM, RBs, and multimedia users. The

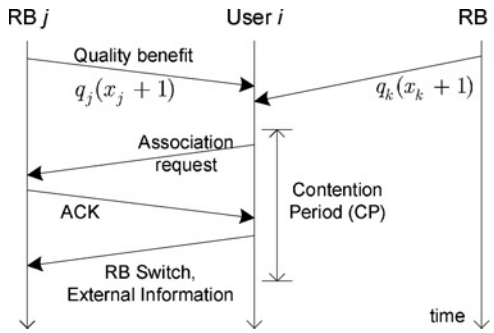


Fig. 2. Example of interactions between RBs and a user.

CRM manages the total available resources[1] based on its regulation policies and regulates how the network resources should be divided among multiple RBs.[2] The allocated resources to N RBs are denoted by $R_1, \ldots, R_N$. Each RB j $(1 \le j \le N)$ allocates its resource R_j to the users in its subnetwork C_j. The allocated resources to the users are denoted by $r_1^j, \ldots, r_{|C_j|}^j$, where $|C_j|$ denotes the number of users in the subnetwork C_j and $\sum_{i=1}^{|C_j|} r_i^j \le R_j$. In this paper, we mainly focus on the interactions among the RBs and the users in the system. The features of the RBs and the users are briefly summarized below.

1) *RBs:* to provide incentives to multimedia users to join their subnetworks, RBs need to "advertise" guaranteed minimum quality which they can provide to various users. Hence, they need to deploy resource allocation solutions that explicitly consider the multimedia quality. This can be achieved by deploying the axiomatic bargaining solutions, which can guarantee a certain level of multimedia quality in a subnetwork. Different bargaining solutions enable RBs to provide various resource management policies.

2) *Users:* multimedia users select the RB, which can provide them the highest guaranteed minimum video quality. Hence, users only need to consider the guaranteed minimum quality that can be provided by a subnetwork, when they join a subnetwork. In addition, a user can switch to another subnetwork if it can improve its guaranteed minimum quality from the current guaranteed minimum quality.

An illustrative example for the interactions among the RBs and the users is depicted in Fig. 1, and detailed protocol design is discussed in Section II-B.

B. Proposed Protocol for Brokerage-Based Resource Management

In this section, we discuss what is the information that needs to be exchanged between the RBs and the users, and how the RBs and the users interact with each other. Then, we study how the RBs allocate the available resources to their associated users.

[1]For example, a central authority in existing wireless LAN [5] and cognitive radio network [6], can be the CRM.

[2]In this paper, we consider two illustrative policies for the CRM: the *unlicensed* policy $\mathcal{G}_u$ and the *licensed* policy $\mathcal{G}_l$. Details are discussed in Section VI.

1) *Initial Information Exchanges:* In the system initialization, every RB gathers characteristics of multimedia users registered to the system, in order to identify their utility functions. Then, an RB j calculates the *quality benefit* $q_j(x_j)$, which is the information about the guaranteed minimum quality, for the number of users x_j in subnetwork based on available resources, utility functions, and the deployed resource division policy $\mathcal{F}^j$. In this paper, we consider the quality-driven resource division policy $\mathcal{F}^j$ as the KSBS or the EBS.

2) *Protocol for Interactions Between RBs and Users:* The interactions between the RBs and the users are illustrated in Fig. 2. The details are described as follows.

a) Each RB j $(1 \le j \le N)$ broadcasts its quality benefit $q_j(x_j+1)$ to multimedia users in the system, such that the users can switch subnetworks based on the announced quality benefits. The design of quality benefit based on the KSBS and the EBS is discussed in Section III-D.

b) Based on the advertised $q_j(x_j+1)$ by RB j $(1 \le j \le N)$, multimedia user i associates itself with specific RB j that can maximize its guaranteed minimum quality, which depends on the deployed resource division policy $\mathcal{F}^j$ in RB j. Specifically, the user i currently in the subnetwork C_j with x_j users will stay in, or switch to the subnetwork $C_{j'}$ currently with $x_{j'}$ users such that

$$j' = \arg \max_{j' \in \{1,\ldots,N\}} \left\{ \underline{Q}_i(q_{j'}(x_{j'}+1)) \right\} > \underline{Q}_i(q_j(x_j))$$

where guaranteed minimum quality $\underline{Q}_i(q_{j'}(x_{j'}+1))$ is computed by the user i using the advertised quality benefit $q_{j'}(x_{j'}+1)$. We discuss how to compute $\underline{Q}_i(q_{j'}(x_{j'}+1))$ in Section III. Then, user i sends its association request to the selected RB.

c) RB j receives the association requests from users and allows one user i to join, in order to guarantee the announced quality benefit. RB j sends ACK to selected user i to notify that user i can join its subnetwork. Then, user i sends RB j its *external information* γ_i^j, which depends on its deployed resource division policy $\mathcal{F}^j$. The external information can be each user's desired maximum quality, utility function parameters including minimum required quality, channel condition, etc. Based on the collected external information, the RB allocates its available resources to the users in its subnetwork.

3) *Protocol for Resource Allocation of RBs in Subnetworks:* The resources can be coordinated using a polling-based MAC protocol similar to IEEE 802.11a Point Coordination Function (PCF) and IEEE 802.11e Hybrid Coordination Function (HCF) [13]. General descriptions for the polling-based MAC protocols can be found in, e.g., [5].

a) An RB j decides the resource allocation $(r_1^j, \ldots, r_{|C_j|}^j)$ based on the gathered external information from users $\mathbf{\Gamma}^j = (\gamma_1^j, \ldots, \gamma_{|C_j|}^j)$ in its subnetwork C_j, and the deployed resource division policy $\mathcal{F}^j : \mathbf{\Gamma}^j \to \mathbb{R}_+^{|C_j|}$ defined as

$$\mathcal{F}^j(\gamma_1^j, \ldots, \gamma_{|C_j|}^j) = (r_1^j, \ldots, r_{|C_j|}^j)$$

where $\sum_{i=1}^{|C_j|} r_i^j \le R_j$. The external information ($\mathbf{\Gamma}^j$) is used to identify their multimedia characteristics.

b) Based on the determined resource allocation $(r_1^j, \ldots, r_{|C_j|}^j)$, RB j polls users in its subnetwork by sending CF-Poll.

c) When users are polled by their RBs (i.e., receiving CF-Poll from their RBs), they start to transmit video data and send CF-ACK to their RBs. While transmitting their data, they also receive the quality benefits announced by the RBs. Based on the announced quality benefits, the users can decide whether they switch subnetworks or not in, for example, contention period (CP).

Note that in the above resource allocation of the RBs, we assume that users truthfully declare their external information. This is an implicit assumption used in most networked resource management schemes and currently implemented in practice (e.g., Ethernet and IEEE 802.11 Standards [5], [13]). However, this assumption might not always be true (see, e.g., [20]), and incentives or penalties might be then needed for the users to declare their private information (i.e., external information) correctly. This can be implemented by deploying mechanism designs, which enforce the users to truthfully declare their external information (see, e.g., [21]). We also note that to negotiate the traffic specification (TSPEC) with the RB, a similar negotiation mechanism such as that of IEEE 802.11e [13], [22] can be used. For each video, a user will transmit a TSPEC containing several parameters such as the peak data rate, the mean data rate, the maximum permissible delay, etc. Besides these parameters, users will also transmit the desired maximum quality ($Q_{\mathrm{MAX}}^{\mathrm{des}}$), the minimum required quality ($Q^{\min}$), and the multimedia characteristics using SDP (session description protocol). A practical implementation of these information exchanges using the protocols is discussed in Section VI-D. Details for video streaming over IEEE 802.11e can be found in [22].

In the next section, we propose the quality-aware admission control algorithms that can be implemented in RBs, using the axiomatic bargaining solutions.

III. Design of Quality-Aware Admission Control Policy

A. Utility Design based on Multimedia Quality

In this paper, we assume that users adhere to a certain video profile (e.g., MPEG-4 profiles), which defines the spatio-temporal video resolution as well as the ranges of bit rates supported. Hence, only users adopting the video profile advertised by the RB can adhere to it. We define the utility function representing the multimedia quality for resource allocation as follows:

$$U_i(r_i(SNR_i)) = \begin{cases} 0, & \text{if } r_i(SNR_i) < r_i^{\mathrm{req}} \\ \frac{c}{D_i(r_i(SNR_i))}, & \text{otherwise} \end{cases} \tag{1}$$

where $U_i(r_i(SNR_i))$ denotes the utility for allocated rate $r_i(SNR_i)$ given the experiencing channel condition SNR_i to user i and c is a positive constant [22]. r_i^{req} represents the user i's specific required minimum rate to achieve its required minimum quality. The $D_i(r_i(SNR_i))$ represents the distortion of multimedia content, measured as the mean square error between the original video and the reconstructed video at the rate $r_i(SNR_i)$. The distortion can be modeled based on rate-distortion functions for video sequences [10]. Based on this definition of the utility function, we deploy a widely used quality measure for video transmission, peak signal to noise ratio (PSNR), defined as

$$\begin{aligned} Q_i(r_i(SNR_i)) &= 10\log_{10}\frac{255^2}{D_i(r_i(SNR_i))} \\ &= 10\log_{10} U_i(r_i(SNR_i))|_{c=255^2} \end{aligned} \tag{2}$$

where $Q_i(r_i(SNR_i))$ denotes the PSNR for user i. Hence, user i's minimum required rate r_i^{req} in (1) satisfies $Q_i(r_i^{req}) = Q_i^{\min}$, where $Q_i^{\min}$ is the minimum required video quality of user i. The *desired* maximum quality of a multimedia user, where achieving higher quality than this does not improve user's visual impact, is denoted by $Q_{\mathrm{MAX}}^{\mathrm{des}}$.

B. Definitions of Bargaining Solutions

In axiomatic bargaining theory, a solution is selected out of the set of possible resource allocation choices that satisfies a set of rational and desirable axioms. More details on the general axiomatic bargaining theory can be found in [23]. Consider a subnetwork with n multimedia users, where resource R is available in the subnetwork. Let $\mathbf{S} = \{U_1(r_1), \ldots, U_n(r_n) | \sum_{l=1}^{n} r_l \le R\} \subset \mathbb{R}^n$ be a feasible utility set, which is a set of jointly achievable utility points given possible resource allocations, and let $\mathbf{d}(\in \mathbb{R}^n) \in \mathbf{S}$ be the disagreement point [23]. The disagreement point is determined based on the minimum utilities that are acceptable to the multimedia applications. In our paper, the disagreement point is the origin (i.e., $\mathbf{d} = \mathbf{0}$), which corresponds to the zero utility of users, since a user does not join any subnetworks when its minimum quality requirement is not satisfied. The pair of $(\mathbf{S}, \mathbf{d})$ defines the bargaining problem. A bargaining solution is a function $F : (\mathbf{S}, \mathbf{d}) \to \mathbb{R}^n$, which determines a unique utility point in $\mathbf{S}$, i.e., $\mathbf{X}^* = (X_1^*, \ldots, X_n^*) = F(\mathbf{S}, \mathbf{d}) \in \mathbf{S}$, where $X_i = U_i(r_i)$ denotes a utility of user i. Different utility points can be determined based on the fairness axioms of deployed bargaining solutions. In this paper, we consider two bargaining solutions, the KSBS and the EBS, defined as follows:

Definition 1 (KSBS): $\mathbf{X}^* = (X_1^*, \ldots, X_n^*) = F(\mathbf{S}, \mathbf{d})$ is said to be a KSBS in $\mathbf{S}$ for $\mathbf{d}$, if

$$\mathbf{X}^* = \max_{\mathbf{X}} \left\{ \mathbf{X} \in \mathbf{S} \;\middle|\; \frac{X_1 - d_1}{X_{\mathrm{MAX}}^1 - d_1} = \cdots = \frac{X_n - d_n}{X_{\mathrm{MAX}}^n - d_n} \right\}$$

where $X_i > d_i$ for all i, and $X_{\mathrm{MAX}}^i = \max_{X_i \in \mathbf{S}, X_i \ge d_i} X_i$. The point $(X_{\mathrm{MAX}}^1, \ldots, X_{\mathrm{MAX}}^n)$ is called the *ideal point*.

Definition 2 (EBS): $\mathbf{X}^* = (X_1^*, \ldots, X_n^*) = F(\mathbf{S}, \mathbf{d})$ is said to be an EBS in $\mathbf{S}$ for $\mathbf{d}$, if

$$\mathbf{X}^* = \max_{\mathbf{X}} \{\mathbf{X} \in \mathbf{S} | X_1 - d_1 = \cdots = X_n - d_n\} \tag{3}$$

where $X_i > d_i$ for all i. In the above definitions, the vector comparison is defined as component-wise comparison. For example, $\mathbf{X} = (X_1, \ldots, X_n) \ge \mathbf{Y} = (Y_1, \ldots, Y_n) \Leftrightarrow X_i \ge Y_i$ for $1 \le i \le n$. The fairness axioms for the KSBS and the EBS can be found in [8] and [9], respectively. In the next section, we discuss how these bargaining solutions can be deployed in RBs for quality-aware resource allocations.

C. Bargaining Solutions for Multimedia Users

As shown in [16], if the KSBS is deployed for the quality-driven resource division policy in an RB, then the quality drop from the *maximum achievable* quality of every user in the subnetwork is the same. However, in multimedia applications, achieving a PSNR level higher than a certain quality threshold (e.g., 40 dB PSNR) is not meaningful, because it does not impact the visual quality. Hence, we assume that each user has its own *desired* maximum quality level at which it will prefer to operate.[3] Based on this assumption, the KSBS maintains the property that the quality drop from the desired maximum quality level is also the same, which is described in the following lemma.

Lemma 1: If the KSBS is deployed for the quality-driven resource division policy in an RB and each user has its own *desired* maximum quality, then the quality drop from the *desired* maximum quality of every user in the subnetwork of an RB is the same.

Proof: Let $(\hat{Q}^1_{\text{MAX}}, \ldots, \hat{Q}^{|C_j|}_{\text{MAX}})$ be the desired maximum quality for every user in the subnetwork C_j determined by users' strategy σ. Since the desired maximum quality cannot exceed the achievable maximum quality for user i (i.e., $\hat{Q}^i_{\text{MAX}} > Q^i_{\text{MAX}}$ is not allowed), we assume that $\hat{Q}^i_{\text{MAX}} \le Q^i_{\text{MAX}}$. Hence, based on (2), the ideal point corresponding to desired maximum quality is $(\hat{X}^1_{\text{MAX}}, \ldots, \hat{X}^{|C_j|}_{\text{MAX}})$, and the KSBS $X_{\text{KSBS}} = (\hat{X}^*_1, \ldots, \hat{X}^*_{|C_j|}) \in \mathbf{S}$ is expressed as $\hat{X}^*_1/\hat{X}^1_{\text{MAX}} = \cdots = \hat{X}^*_{|C_j|}/\hat{X}^{|C_j|}_{\text{MAX}}$, where $\hat{X}^*_i > d_i = 0$ for all i. This is equivalent to

$$\triangle\hat{Q}^{\text{drop}}(|C_j|, \sigma) \triangleq \triangle\hat{Q}^{\text{drop}}_1 = \cdots = \triangle\hat{Q}^{\text{drop}}_{|C_j|} \tag{4}$$

where $\triangle\hat{Q}^{\text{drop}}_i \triangleq \hat{Q}^i_{\text{MAX}} - \hat{Q}^*_i$ is the quality drop from user i's desired maximum quality, and $\hat{Q}^*_i = 10\log_{10}\hat{X}^*_i$ denotes the achievable quality determined by the KSBS. ■

We now investigate the quality-driven resource division policy based on the EBS. As we described above, each multimedia user is assumed to have its own desired maximum quality level. The following lemma shows that the EBS has the property of equal achievable quality if users have their desired maximum quality.

Lemma 2: If the EBS is deployed for the quality-driven resource division policy in a RB and each user has its own *desired* maximum quality, then the achievable quality of every user in the subnetwork of an RB is the same.

Proof: Let $(\widetilde{Q}^1_{\text{MAX}}, \ldots, \widetilde{Q}^{|C_j|}_{\text{MAX}})$ be the desired maximum quality for every user in the subnetwork C_j determined by users' strategy σ, and $\mathbf{S}$ denotes the feasible utility set. We also assume that $\widetilde{Q}^i_{\text{MAX}} \le Q^i_{\text{MAX}}$. Hence, this desired maximum quality only affects the feasible utility set, possibly forming a subfeasible utility set $\mathbf{S}'$ of the original feasible utility set $\mathbf{S}$, i.e., $\mathbf{S}' \subseteq \mathbf{S}$. Therefore, based on (2) and (3), $X_{\text{EBS}} = (\widetilde{X}^*_1, \ldots, \widetilde{X}^*_{|C_j|}) \in \mathbf{S}'$, $\widetilde{X}^*_i > 0$ for all i, is expressed as $\widetilde{X}^*_1 = \cdots = \widetilde{X}^*_{|C_j|}$ which directly leads to

$$\widetilde{Q}^*(|C_j|, \sigma) \triangleq \widetilde{Q}^*_1 = \cdots = \widetilde{Q}^*_{|C_j|} \tag{5}$$

where $\widetilde{Q}^*_i$ is the achievable quality of user i. ■

[3] This point can also be determined based on the amount of money (tax) the users want to pay for a certain video quality, but this goes beyond the scope of this paper.

D. Quality Benefit: Guaranteed Minimum Quality

Based on *Lemma 1* and *Lemma 2*, RBs can compute the guaranteed minimum quality to every associated multimedia user that has its own desired maximum quality.

Based on *Lemma 1*, if a RB deploys the KSBS as a quality-driven resource division policy, the quality drop from the desired maximum quality of each user is the same in the subnetwork. Hence, the RB can determine the maximum quality drop for a certain number of users by considering all possible combinations. The minimum quality for x_j users guaranteed by an RB j that deploys the KSBS can be computed as

$$q^{\text{KSBS}}_j(x_j) \triangleq \min\left\{ -\triangle\hat{Q}^{\text{drop}}(x_j, \sigma) \,\middle|\, x_j = |C_j| \text{ for all } \sigma \right\}. \tag{6}$$

Therefore, the RB j that currently supports x_j users can advertise quality benefit $q^{\text{KSBS}}_j(x_j + 1)$ to the users in the network. Based the quality benefit advertised by RB j, a user i can compute the guaranteed minimum quality by joining subnetwork C_j as

$$\underline{Q}_i(q^{\text{KSBS}}_j(x_j + 1)) = \hat{Q}^i_{\text{MAX}} + q^{\text{KSBS}}_j(x_j + 1) \tag{7}$$

where $\hat{Q}^i_{\text{MAX}}$ denotes the user i's desired maximum quality.

Similarly, based on *Lemma 2*, if an RB deploys the EBS, the achieved quality for users is the same in the subnetwork. Thus, the RB is able to guarantee an minimum achievable quality given a certain number of users. The minimum quality for x_j users guaranteed by an RB j that deploys the EBS can be computed as

$$q^{\text{EBS}}_j(x_j) \triangleq \min\left\{ \widetilde{Q}^*(x_j, \sigma) \,\middle|\, x_j = |C_j| \text{ for all } \sigma \right\}. \tag{8}$$

Therefore, the RB j that currently supports x_j users can advertise $q^{\text{EBS}}_j(x_j + 1)$ to the users in the network. Thus, user i's guaranteed minimum quality by the RB j can be expressed as

$$\underline{Q}_i(q^{\text{EBS}}_j(x_j + 1)) = q^{\text{EBS}}_j(x_j + 1). \tag{9}$$

Summarizing, RBs deploying the KSBS or the EBS can advertise their guaranteed minimum quality by announcing the quality benefits.

IV. Congestion Game Modeling for Selecting Resource Brokers

In this section, we model the discussed admission control scheme as a quality-driven congestion game, which will have the important advantage that multimedia users can converge to a stationary distribution across RBs. The players in this game are the multimedia users, and they strategically make their own decisions (i.e., RB selections) by considering the announced quality benefits. Specifically, each user determines its RB selection and sends its association request to the selected RB.

Then, each RB accepts only one request among (possibly) multiple association requests from the users. Therefore, this enables only one user to switch between RBs at any given time. We begin by defining congestion games for the proposed admission control scheme. The original definition of congestion games can be found in [24]. Recall that the proposed admission control scheme consists of N RBs and n users.

Definition 3 (Congestion Game for Proposed Approach): A *congestion game* for the proposed admission control is a tuple $\langle M, (\Omega_i)_{i\in M}, (u_i)_{i\in M}\rangle$, where M is a nonempty set of users and $(\Omega_i)_{i\in M}$ is a nonempty set of RBs available for user $i \in M$. For $i \in M$, $u_i : \Omega \to \mathbb{R}$ is defined by

$$u_i(\sigma) = c_{\sigma_i}(n_{\sigma_i}(\sigma)) \tag{10}$$

where $\sigma = (\sigma_1, \ldots, \sigma_n) \in \Omega = \times_{i\in M}\Omega_i$ denotes the set of selected RBs by the users, and $n_{\sigma_i}(\sigma)$ is the number of users associating with RB σ_i if the users choose σ. For each RB σ_i, $c_{\sigma_i}(k)$, $k \in \{1, \ldots, n\}$, denotes the benefits to each user in RB σ_i if there is a total of k users.

Note that the benefit function $c_{\sigma_i}(\cdot)$ in *Definition* 3 is only a function of the number of users in RB σ_i. Hence, to model the proposed admission control schemes as a congestion game, we will focus on designing the benefit function such that it is a function of the number of users in RBs in the following sections.

A. Resource-Driven Congestion Game

In this section, we consider, as a reference for the algorithms proposed in the next section, that the admission control scheme can be modeled as a resource-driven congestion game. Hence, there exists a PSNE, i.e., a stationary distribution of users [24].

Definition 4 (Equal Resource Allocation, ERA): Resources R are allocated to n users by the *ERA* if

$$r_i = R/n, \text{ for } i = 1, \ldots, n$$

where r_i denotes the allocated resource for user i.

Since in our system each user can join only one of the subnetworks, each user i can select $\sigma_i \in \Omega_i$, which represents the index of subnetwork of the RB that the user i joins. Hence, the benefit for user i by joining the subnetwork C_j (i.e., $\sigma_i = j$) can be expressed as

$$u_i(\sigma) = c_{\sigma_i}(n_{\sigma_i}(\sigma)) = c_j(n_j(\sigma)). \tag{11}$$

As an illustrative example, we will show that if the ERA is deployed for a resource division policy in an RB, then the admission control scheme can be modeled as an unweighted congestion game. Let $(R_1, \ldots, R_N)$ be a resource allocation for all subnetworks of RBs based on a deployed policy $\mathcal{G}$ of the CRM, and $\sigma_i \in \{1, \ldots, N\}$ denotes the selection of RB (action) for user i. Since RB j deploys the ERA as a fairness policy $\mathcal{F}_{ERA}$, the benefit of user i by joining the subnetwork of the RB j (i.e., $\sigma_i = j$) is expressed as

$$u_i(\sigma) = c_j(n_j(\sigma)) = c_j(x_j) = R_j/x_j$$

where $x_j = n_j(\sigma)$ represents the number of users in subnetwork C_j. Note that the benefit function $c_j(x_j) = R_j/x_j$ is only a function of the number of users in a subnetwork. Therefore, this resource allocation scheme can be modeled as a congestion game. In addition, since this resource allocation scheme is an unweighted congestion game, there exists at least one PSNE [24], if the ERA is deployed for the resource-based fairness policy in an RB.

In [16], it was shown that resource-based allocation strategies are not efficient for multimedia because they do not explicitly consider the video qualities. Therefore, we need to consider *quality-driven* resource allocation, as discussed in the next section.

B. Quality-Driven Congestion Games

In this section, we model the proposed network managed by the quality-driven resource division policies based on bargaining solutions as congestion games. The congestion games defined in *Definition 3*, where the RBs deploy quality-driven resource division policies, are referred to as *quality-driven congestion games* in this paper. The deployed bargaining solutions (the KSBS and the EBS) can provide the desired relationship between the qualities of autonomous and rational multimedia transmitting users.[4]

As we showed in *Lemma 1* and *Lemma 2*, the KSBS and the EBS are adequate for autonomous multimedia users as they provide fairness criteria that guarantee the same quality drop from the desired maximum quality for all users and the same achievable quality for all users, respectively. Also, they enable RBs to advertise the guaranteed minimum quality that they can provide to a multimedia user by considering only the number and not the specific characteristics (multimedia and channel characteristics) of users present in the network. Hence, it enables us to model the problem of network resource allocation to multimedia users using resource brokers as a quality-driven unweighted congestion game. This is described in the following proposition.

Proposition 1: In multimedia wireless networks, if the KSBS (or the EBS) is deployed as quality-driven resource division policy in all RBs with *desired* maximum qualities, then the proposed admission control scheme is a quality-driven unweighted congestion game.

Proof: To model the proposed admission control scheme as an unweighted congestion game, the benefit function should be only a function of the number of users in RBs as discussed in (11). This can be achieved by using the quality benefit functions defined in (6) and (8).

By *Lemma 1*, if all RBs deploy the KSBS as a quality-driven resource division policy, the quality drop from the desired maximum quality of each user is the same in a subnetwork. Hence, the maximum quality drop for a user i in RB j can be considered as a benefit, expressed as

$$u_i(\sigma) = c_{\sigma_i}(n_{\sigma_i}(\sigma)) = c_j(n_j(\sigma)) = c_j(x_j) = q_j^{\text{KSBS}}(x_j).$$

Since the desired maximum utilities are determined by users and they are fixed, users only consider the quality benefits

[4]The NBS, which is the other well-known bargaining solution, cannot be efficiently used for noncollaborative multimedia applications as it maximizes the sum of qualities from all rather than focus on the individual quality of each user [16].

announced by RBs, i.e., each user chooses the subnetwork guaranteeing the largest quality benefit.

Similarly, if all RBs deploy the EBS as a quality-driven resource division policy, the achieved quality for users is the same in the subnetworks by *Lemma 2*. Hence

$$u_i(\sigma) = q_j^{\text{EBS}}(x_j). \tag{12}$$

Since the disagreement point is the origin, each user chooses the RB which guarantees the largest quality benefit for a certain number of users in the subnetwork.

As shown in (6) and (8), the quality benefit function $q_j(x_j)$ is only a function x_j and $q_j(x_j)$ is nonincreasing function. Therefore, the proposed admission control scheme with the KSBS or the EBS can be modeled as a quality-driven unweighted congestion game. ■

Since an unweighted congestion game ensures at least one PSNE [24], it is concluded that the proposed brokerage-based admission control scheme has a PSNE, i.e., a stable distribution of multimedia users over RBs. We note that an unweighted congestion game is also an exact potential game that admits a potential function [24]. We will define the potential function and deploy it to show the net increment of the quality benefit in Section V-B. In the next section, we will investigate the properties of the PSNE and in the result section, we will show how users converge to a PSNE.

V. Properties of the PSNE

A. Speed of Convergence

In this section, we investigate the speed of convergence for the quality-driven congestion game. From the previous section, we already know that there should be at least one PSNE. Hence, the next question is how *fast* a PSNE is reached. As discussed in Section II-B, each RB allows only one user to join if there are multiple association requests, in order to ensure the announced quality benefit.[5] This can be modeled as an Elementary Stepwise System (ESS), where each user switches its subnetwork sequentially [25]. If multiple users are allowed to switch subnetworks simultaneously, a stationary distribution of users may not be ensured due to problems of repeatedly switching resource brokers. This issue has been discussed in several works (e.g., [26]). A simple illustration is given in Fig. 3, which shows the number of users in subnetworks if multiple users are allowed to switch simultaneously (a) or ESS is implemented (b). Based on this system model, we show next that a PSNE can be achieved at most $(n-1)$ users' switches.

Lemma 3: If every RB deploys the KSBS (or the EBS) as a resource division policy, then a user switches subnetworks at most once.

Proof: Let $\mathbf{Q}$ be $n \times N$ matrix of all quality benefits for n users and N RBs, defined as

$$\mathbf{Q} = \begin{bmatrix} q_1(1) & \dots & q_N(1) \\ \vdots & \ddots & \vdots \\ q_1(n) & \dots & q_N(n) \end{bmatrix} \tag{13}$$

[5]The RBs can deploy a user selection criterion, where the user having the highest quality benefit improvement can be selected. However, other selection criteria can also be deployed.

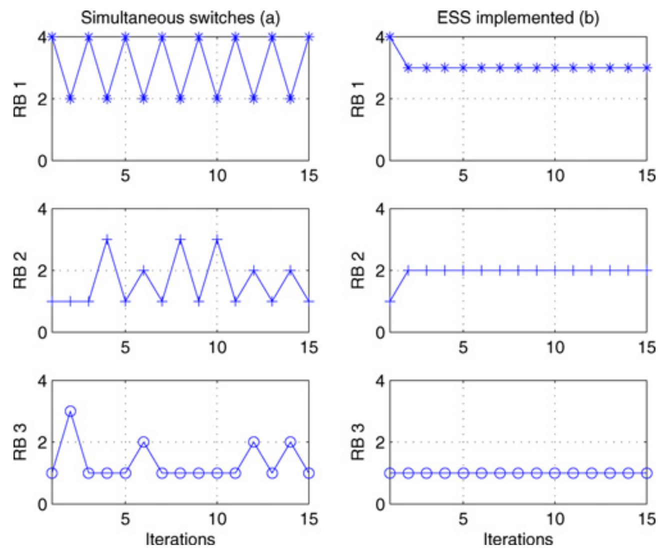


Fig. 3. Number of users in subnetworks over time when users are allowed to (a) switch simultaneously or (b) ESS is implemented. EBS is deployed in each RB. The quality benefits are $q_1^{\text{EBS}}(x_1) = [35, 34, 33, 30]$ and $q_2^{\text{EBS}}(x_2) = q_3^{\text{EBS}}(x_3) = [35, 32, 31, 30]$ for $n = 6$ users. One switch is required for users in ESS to converge to a PSNE for user's initial distribution (4, 1, 1).

where $q_j(x_j)$ for the KSBS and the EBS are defined in (6) and (8), respectively. Note that $q_1(1) = \cdots = q_N(1)$, as only one user in a subnetwork can have no quality drop from its desired maximum quality (if the KSBS is deployed) or derive the desired maximum quality (if the EBS is deployed). Furthermore, notice that $q_j(x_j)$ is a nonincreasing function of the number of users x_j in the subnetwork C_j since the available resource for an RB is fixed and it is shared with users in the subnetwork. Let $\mathbf{q}_k$ be the set of quality benefits announced by all the RBs after k switches of users, called *quality benefit status*. It is defined as

$$\mathbf{q}_k = \{q_1(y_1+1), \ \dots, \ q_N(y_N+1)\} \tag{14}$$

and $\mathbf{q}_k$ can be transmitted from RBs to users. Note that (14) implies y_j users are currently in the subnetwork C_j, and a user that additionally joins subnetwork C_j will have the quality benefit $q_j(y_j+1)$ for all y_j such that $\sum_{j=1}^{N} y_j \le n$, and $0 \le y_j \le n$.

Since every user is autonomous, it is trying to switch to the subnetwork which can provide it a higher quality benefit as opposed to the current one. Therefore, a user i in the subnetwork C_w chooses the subnetwork C_v if and only if

$$\begin{aligned} q_w(y_w) < q_v(y_v+1) &= \max\{q_1(y_1+1), \dots, q_N(y_N+1)\} \\ &= \max\{\mathbf{q}_k\}. \end{aligned} \tag{15}$$

After $(k+1)$ switches (i.e., one more switch of the user i after k switches), the quality benefit status $\mathbf{q}_{k+1}$ is expressed as

$$\begin{aligned} \mathbf{q}_{k+1} = \{&q_1(z_1+1), \dots, q_v(z_v+1), \\ &\dots, q_w(z_w+1), \dots, q_N(z_N+1)\} \end{aligned}$$

where $z_j = y_j$ for all j except w and v. Since the user i switches from the subnetwork C_w to the subnetwork C_v,

$z_v = y_v + 1$ and $z_w = y_w - 1$. And $\sum_{j=1}^{N} z_j \leq n$ and $0 \leq z_j \leq n$ for $j = 1, \ldots, N$ since there is no change of the total number of users.

Another user i' in the subnetwork $C_{w'}$ after $(k+1)$ switches chooses the subnetwork $C_{v'}$ if and only if

$$q_{w'}(z_{w'}) < q_{v'}(z_{v'} + 1) = \max\{\mathbf{q}_{k+1}\}. \quad (16)$$

Note that $q_{v'}(z_{v'} + 1) \leq q_v(y_v + 1)$, since

$$\begin{aligned} & q_{v'}(z_{v'} + 1) \\ & \quad = \max\{q_1(z_1 + 1), \ldots, q_v(z_v + 1), \\ & \qquad \ldots, q_w(z_w + 1), \ldots, q_N(z_N + 1)\} \quad (17) \\ & \quad = \max\{q_1(y_1 + 1), \ldots, q_v(y_v + 2), \\ & \qquad \ldots, q_w(y_w), \ldots, q_N(y_N + 1)\} \quad (18) \\ & \quad \leq \max\{q_1(y_1 + 1), \ldots, q_v(y_v + 1), \\ & \qquad \ldots, q_w(y_w), \ldots, q_N(y_N + 1)\} = q_v(y_v + 1) \end{aligned}$$

where the inequality for (17) and (18) is from the fact that $q_j(x_j)$ is nonincreasing function, and the solution for (18) is from (15). Based on the fact that $q_{v'}(z_{v'} + 1) \leq q_v(y_v + 1)$, and (15) and (16), we can conclude that

$$\max\{\mathbf{q}_k\} \geq \max\{\mathbf{q}_{k+1}\} \quad (19)$$

which implies that once a user switches to the subnetwork that provides the largest quality benefit at that moment, the user will not switch to other subnetworks in the future, because the user cannot improve quality benefit by switching subnetworks. Hence, a user will switch subnetworks at most once. ■

Lemma 3 directly leads to the following theorem.

Theorem 1: If every RB deploys the KSBS (or the EBS) as a resource division policy, then the required number of subnetwork switches for n users to reach a PSNE is at most $(n - 1)$.

Proof: As *Lemma 3* shows, a user will switch at most once. Since there are n users and $q_1(1) = \cdots = q_N(1)$, users will not switch after at most $(n - 1)$ switches. ■

From *Theorem* 1, we conclude that the required number of subnetwork switches for users to reach a PSNE has the upper bound of $(n - 1)$, which is linear to the number of users. Therefore, the users will be in a stationary distribution across the RBs after at most $(n - 1)$ switches. These results can be extended to the case, where new n' users participate in this network after a PSNE is already established. Since the network is already at a PSNE, the only required steps to reach another new PSNE with n' users are to switch to the subnetworks that provide higher quality benefit, which requires at most n' switches. Therefore, it is also concluded that a new PSNE is achieved in one switch when a new user is joining the network that is already in a PSNE.

B. Net Quality Benefit From Switching RBs

As mentioned before, a user switches to another RB if it can derive a larger quality benefit as opposed to staying in the current RB. Then, the next question is how much quality benefit a user can achieve by changing subnetworks at every step. We can show the net increment of quality benefit by using a potential function [24] defined in our case based on the quality as

$$\Phi(\sigma) = \sum_{j \in \cup_{i=1}^{n} \sigma_i} \sum_{x=1}^{x_j} q_j(x) \quad (20)$$

where $\sigma = (\sigma_1, \ldots, \sigma_n)$ is the set of strategies of n users, and x_j is the number of users in a subnetwork C_j. Based on the property of the potential function, where one user's change of the function value by its unilateral strategy deviation is the same as the utility value change, if user i switches to the other subnetwork, it tracks the change of quality benefit corresponding to the switch of user i's subnetwork. Therefore, the net gain of quality benefit by changing the subnetwork is the increase of the potential function corresponding to this strategy change. Specifically, given quality benefits $q_w(y_w)$ and $q_v(y_v)$ of subnetwork C_w and C_v, if user i unilaterally change its strategy from $\sigma_i = w \in \sigma$ to $\sigma_i = v \in \sigma'$, the corresponding quality benefit increment of user i becomes $q_v(y_v+1)-q_w(y_w)$, and by the property of the potential function, this quality benefit increment can be expressed as

$$q_v(y_v + 1) - q_w(y_w) = \Phi(\sigma') - \Phi(\sigma). \quad (21)$$

Since all quality benefits corresponding to the number of users are available, the potential function enables us to quantify the quality benefit that can be obtained by a user by changing its strategy. Moreover, this potential function can be used as the criteria for users to decide whether to switch to another subnetwork or not. Specifically, a user i will change its strategy from $\sigma_i = w \in \sigma$ to $\sigma_i = v \in \sigma'$ if

$$\Phi(\sigma') - \Phi(\sigma) > \delta_i \quad (22)$$

where δ_i denotes the quality threshold for the user i (e.g., user i switches subnetworks if the quality benefit improvement is larger than 1 dB). Hence, for example, a multimedia user i only trying to maximize its guaranteed qualities can set $\delta_i = 0$, i.e., it will switch from its current subnetwork to the other subnetwork as long as the other subnetwork provides a higher quality benefit. Hence, we assume that each user can have its own quality threshold to determine whether it is worthwhile to switch subnetworks. Note that, as explained in Section II-B, the RBs can use each user's quality threshold as a user selection criterion. For example, an RB j can select the user with the highest threshold among users that request to switch to RB j, since the user's subnetwork switch may result in the largest quality improvement. The impact of users' thresholds on the number of switches required for a convergence is quantitatively evaluated in Section VI-C.

C. Fairness Comparison in Terms of Multimedia Quality

Until now, we have analyzed a quality-driven congestion game, and discussed its speed of convergence for reaching a PSNE. In this section, we quantify how fair this PSNE determined by decentralized users' switches is compared to a centralized fair solution.

To quantify how fairly the resources are allocated by the proposed admission control solution at PSNE compared to the centralized fair solution, we introduce a new fairness comparison metric (FCM). In [27], a fairness index is defined to quantitatively evaluate the fairness of an allocation policy by showing how far the allocation is from *equality*, which is the equal allocation of resources. As the fairness index focuses on the deviation of resource allocation from the equality, it does not consider the impact on the derived quality, as we discussed in Section IV-A. Hence, we define the FCM such that it can explicitly represent the *quality deviation* at PSNE from the centralized fair solution.

Since users select their subnetworks based only on the advertised quality benefit, which is the information for guaranteed minimum quality, the *actual quality benefit* $\hat{q}_j$ that users can achieve in RB j based on the deployed bargaining solution is higher than the advertised quality benefit. Moreover, since a PSNE is also determined by the advertised quality benefit (not the actual quality benefit), there might be discrepancy between the PSNE and the centralized fair solution. To quantify the fairness of PSNE for multimedia networks, we define the centralized fair solution as

$$\sigma^* = \arg\min_{\sigma} \left\{ \sum_{j=1}^{N} n_j(\sigma) \cdot |\hat{q}_j(\sigma) - \bar{\hat{q}}| \right\} \tag{23}$$

which represents the strategy of multimedia users to select resource brokers that provides the smallest deviation from the mean of the actual quality benefit of users over all resource brokers (i.e., $\bar{\hat{q}} = 1/N \sum_{j=1}^{N} \hat{q}_j$). Moreover, to represent the deviation of the actual quality benefit at PSNE as opposed to that obtained by the centralized fair solution, we define the FCM of RB j as

$$FCM_j = \left| \hat{q}_j(\sigma_{\text{PSNE}}) - q_j(\sigma^*) \right| \tag{24}$$

where σ_{PSNE} denotes the strategy determined by the PSNE. Note that FCM has a value of 0 if the PSNE achieves the centralized fair solution, which is the optimal case for a PSNE. Moreover, the FCM takes larger values as the PSNE provides a less fair solution.

VI. Simulation Results

In this section, we present simulation results for several different resource management scenarios. In our simulations, there are 10 users ($n = 10$) transmitting video sequences and 3 subnetworks ($N = 3$). We assume that each user takes its action (i.e., RB selection) randomly within each CP. Hence, each user waits a random time (which is less than the CP) after receiving the broadcast quality benefits from RBs and send its association request to an RB. Then each RB accepts only one request among (possibly) multiple association request from the users. The CRM allocates the total resources to RBs using two resource allocation policies: *unlicensed* policy $\mathcal{G}_u$, and *licensed* policy $\mathcal{G}_l$. For $\mathcal{G}_u$, the CRM allocates the same amount of resources to each RB, i.e., $R_j = R_{\text{MAX}}/N$, $1 \le j \le N$. For $\mathcal{G}_l$, the CRM allocates the resources proportionally to the number of licensed users to each RB, i.e., $R_j = R_{\text{MAX}} \times L_j / \sum_{l=1}^{N} L_l$, $1 \le j \le N$, where L_j denotes the number of admissible licensed users to the subnetwork C_j. We assume that the licensed number of users for each subnetworks are 5, 4, and 3 when the CRM uses the licensed policy $\mathcal{G}_l$. The total resources are 3 Mb/s ($R_{\text{MAX}} = 3$ Mb/s) for every simulation. We used a state-of-the-art wavelet video coder [28] to compress the video sequences, shown in Table I, with different temporal levels (TL). The detailed parameters can be found in [16], and the user-specific minimum required quality ($Q^{\min}$) and desired maximum quality $Q_{\text{MAX}}^{\text{des}}$ (i.e., $Q_{\text{MAX}}^{\text{des}} = \hat{Q}_{\text{MAX}}$ for the KSBS or $Q_{\text{MAX}}^{\text{des}} = \tilde{Q}_{\text{MAX}}$ for the EBS) for different video sequences are also shown in Table I.

TABLE I
Model Parameters for Video Sequences (Video Type, Temporal Level [TL], Frame Rate)

Video No.	Video Sequence	$Q^{\min}$	$Q_{\text{MAX}}^{\text{des}}$
1	*Foreman* (CIF, TL = 4, 30 Hz)	25 dB	35 dB
2	*Coastguard* (CIF, TL = 4, 30 Hz)	25 dB	35 dB
3	*Mobile* (CIF, TL = 4, 30 Hz)	25 dB	30 dB
4	*Foreman* (QCIF, TL = 4, 30 Hz)	25 dB	33 dB
5	*Foreman* (CIF, TL = 4, 15 Hz)	25 dB	33 dB
6	*Foreman* (CIF, TL = 2, 30 Hz)	25 dB	33 dB

TABLE II
Quality Benefit Matrix **Q**

Q (Unlicensed KSBS)				**Q** (Licensed KSBS)			
x	$j = 1$	$j = 2$	$j = 3$	x	$j = 1$	$j = 2$	$j = 3$
1	0	0	0	1	0	0	0
2	−1.04	−1.04	−1.04	2	−0.01	−1.04	−2.42
3	−2.16	−2.16	−2.16	3	−1.16	−2.16	−3.58
4	−3.05	−3.05	−3.05	4	−2.02	−3.05	$-\infty$
5	−3.84	−3.84	−3.84	5	−2.71	$-\infty$	$-\infty$
Q (Unlicensed EBS)				**Q** (Licensed EBS)			
x	$j = 1$	2	3	x	$j = 1$	2	3
1	30.00	30.00	30.00	1	30.00	30.00	30.00
2	28.96	28.96	28.96	2	29.99	28.96	27.58
3	27.86	27.86	27.86	3	28.85	27.86	26.45
4	26.98	26.98	26.98	4	28.06	26.98	$-\infty$
5	26.22	26.22	26.22	5	27.33	$-\infty$	$-\infty$

A. Required Number of Switches for a PSNE

In this section, we investigate the average number of switches to reach a PSNE. We already showed that the required number of switches is at most $n - 1$, where n is the total number of users in a network. To analyze the average number of switches, we first uniformly distribute all users to all available subnetworks, and then, count the number of switches before reaching a PSNE. This simulation is repeated 100 times. The simulation has four scenarios based on the combination of $\mathcal{G}_u$ or $\mathcal{G}_l$ for the CRM, and the KSBS or the EBS policy for the RBs. Several examples of quality benefit matrix **Q** for these scenarios are shown in Table II.

As expected, the quality benefit functions are nonincreasing functions, and the $q_j(1)$ for $j = 1, 2, 3$ are identical. It is also observed that there are several $-\infty$ in the licensed quality benefits, indicating that only a limited number of users are allowed to join RBs. If the quality benefits are $-\infty$, no user can join this subnetwork. Note that the 10 largest elements of

TABLE III

REQUIRED NUMBER OF SWITCHES FOR A PSNE

CRM Policy	RB Policy	#SW (avg)	Distribution (avg)
Unlicensed ($\mathcal{G}_u$)	KSBS	1.47	(3.34, 3.32, 3.34)
	EBS	1.40	(3.22, 3.38, 3.40)
Licensed ($\mathcal{G}_l$)	KSBS	2.49	(5, 3, 2)
	EBS	2.57	(5, 3, 2)
CRM Policy	RB Policy	#SW (worst)	Distribution (worst)
Unlicensed ($\mathcal{G}_u$)	KSBS	6	(4, 3, 3)
	EBS	6	(4, 3, 3)
Licensed ($\mathcal{G}_l$)	KSBS	8	(5, 3, 2)
	EBS	8	(5, 3, 2)

TABLE IV

STATISTICS OF AVERAGE FCM

	Unlicensed Policy $\mathcal{G}_u$		Licensed Policy $\mathcal{G}_l$	
	Similar	Different	Similar	Different
Mean	0.036	0.488	0.023	0.460
Standard Deviation	0.073	0.210	0.056	0.208

the matrix $\mathbf{Q}$ for unlicensed case are $q_1(1)$, $q_2(1)$, $q_3(1)$, $q_1(2)$, $q_2(2)$, $q_3(2)$, $q_1(3)$, $q_2(3)$, $q_3(3)$, $q_1(4) = q_2(4) = q_3(4)$, and for licensed case are $q_1(1)$, $q_2(1)$, $q_3(1)$, $q_1(2)$, $q_2(2)$, $q_1(3)$, $q_1(4)$, $q_2(3)$, $q_3(2)$, $q_1(5)$. Hence, for the unlicensed policy $\mathcal{G}_u$, we expect that there will be 4, 3, and 3 users in subnetworks at a PSNE. (The subnetwork that has 4 users at a PSNE is determined by the initial distribution of users.) Moreover, for the licensed policy $\mathcal{G}_l$, we expect that there will be 5, 3, and 2 users in each subnetwork. The corresponding results are shown in Table III, where #SW (avg) and #SW (worst) denote the average number of switches and the number of switches in the worst case, respectively.

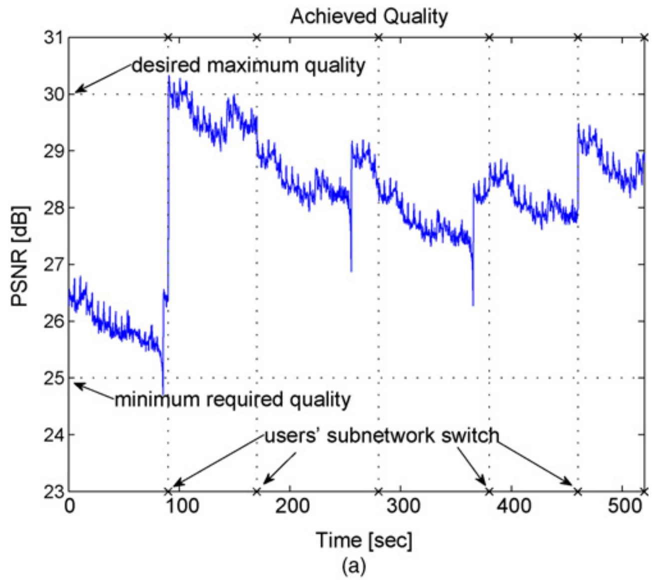
As expected, the average number of users in each subnetwork is almost the same for the unlicensed case, and is exactly the same for the licensed case. Note that the average required number of switches to reach a PSNE is approximately 1.4 and 2.5 for the unlicensed and licensed cases, which are 15.6% and 27.8% compared to the bound (i.e., $n - 1 = 9$).

B. Quantification of PSNE Based on FCM

In this section, we quantify the fairness based on multimedia quality achieved by the PSNE compared to that by the centralized fair solution. Given the expression of the FCM in (24), Table IV shows the simulation results of average FCM across RBs for different CRM policies (i.e., $\mathcal{G}_u$ and $\mathcal{G}_l$) and different multimedia user types (similar and different multimedia transmission).[6]

Since a PSNE is reached based on the advertised quality benefits from RBs, it can achieve the centralized fair solution at most, and the corresponding FCM has its minimum value 0. Recall that the FCM takes larger values as a PSNE leads to a less fair resource allocation. For both CRM policies $\mathcal{G}_u$ and $\mathcal{G}_l$, it is observed that users can achieve the centralized fair solution many more times at a PSNE, when they transmit similar multimedia sequences, than at a PSNE, when they transmit different types of multimedia sequences. This is because transmitting similar video sequences enables RBs to advertise quality benefits similar to the actual quality benefits. However, when users transmit very different multimedia sequences, the FCM value increases, thereby implying a larger deviation from the centralized fair solution. Based on these results, we can conclude that if similar types of users are in a network, users can reach a PSNE which is close to the centralized fair solution.

[6]For "similar" multimedia user scenario, the users randomly select their video sequences between Video No. 1 and Video No. 2 in Table I. For "different" multimedia user scenario, the users can select any video sequences given in Table I.



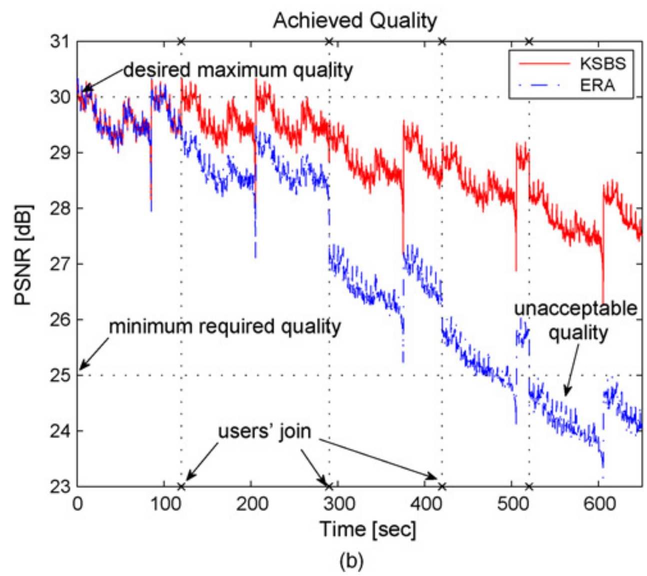


Fig. 4. Derived quality of *Mobile* user over time. Both results present that the derived quality of *Mobile* user over time as (a) users switch subnetworks or (b) join subnetworks. Vertical lines represent the time stamps when users switch or join subnetworks.

C. Resource Broker Switching Criteria

In this section, we analyze the relationship between the required number of subnetwork switches and the switching

TABLE V
QUALITY THRESHOLDS (δ) AND THE AVERAGE REQUIRED NUMBER OF SWITCHES FOR A PSNE

CRM Policy	RB Policy	$\delta = 0$	$\delta = 0.5$ [dB]	$\delta = 1$ [dB]	$\delta = 1.5$ [dB]	$\delta = 2$ [dB]	$\delta = 2.5$ [dB]
Unlicensed	KSBS	1.42 (100%)	1.23 (86.6%)	1.02 (71.8%)	0.71 (50.0%)	0.43 (30.3%)	0.30 (21.1%)
($\mathcal{G}_u$)	EBS	1.39 (100%)	1.34 (96.4%)	1.23 (88.5%)	1.01 (72.7%)	0.54 (38.8%)	0.35 (25.2%)
Licensed	KSBS	2.82 (100%)	2.04 (72.3%)	1.49 (52.8%)	1.41 (50.0%)	1.32 (46.8%)	1.24 (44.0%)
($\mathcal{G}_l$)	EBS	2.58 (100%)	1.87 (72.5%)	1.83 (71.0%)	1.47 (57.0%)	1.08 (41.9%)	1.03 (40.0%)

criteria. As we discussed in Section V-B, users can determine their thresholds as the criteria for switching subnetworks based on their delay requirement, and it is expressed in (22) using the potential function, i.e., $\Phi(\sigma') - \Phi(\sigma) > \delta$. If users try to maximize the achievable quality, they set their quality threshold as 0. However, if users consider only a significant quality improvement, they can set their thresholds correspondingly, which may lead to a faster convergence. We assume that users in a subnetwork have the same quality threshold in these experiments. Simulation results are shown in Table V. In Table V, percentage values are additionally presented in order to easily compare the average numbers of switches. The baseline for the percentage values is the case of $\delta = 0$, where the maximum number of switches is required for convergence.

The simulation results show that the average number of subnetwork switches required to reach a PSNE decreases as the thresholds increase, thereby leading to a faster resource negotiation.

D. Simulation Results Using an IEEE 802.11a/e Test-Bed

In this section, we investigate the multimedia quality which can be derived by a particular user as more users join or switch subnetworks.

We present an implementation of our proposed brokerage-based admission control schemes in an IEEE 802.11a/e wireless test-bed presented in [22]. In the multimedia streaming system, the wireless users can transmit the bitstream compressed by a variety of video coders, including a state-of-the-art wavelet video coder [28]. We used the same setting of the wireless card as in [22] for the required parameters such as the beacon interval (T = 100 ms), the reserved time for the contention period (T_{CP} = 60 ms), and the service interval (T_{SI} = 50 ms), etc.

There are three desktop PCs that act as QoS-enabled APs (QAPs), which are the RBs in this paper. QAPs use distinct channels, channel 1, 6, and 11, respectively. In this experiment, QAPs deploy the KSBS as a resource division policy in their subnetworks, and compute the TXOPs using the received information from users. Each QAP uses SIP (session initiation protocol) to announce its supported video profile and its quality benefit to users and SDP to exchange the minimum required quality ($Q^{\min}$) and desired maximum quality ($Q^{\mathrm{des}}_{\mathrm{MAX}}$). The QAPs also use RTSP (real time streaming protocol) to allow the RBs to inform the users the changes in the quality benefit and the corresponding transmission rates which they can support. Based on this, the wireless users will adjust their bitstream using the multitrack hinting solutions in [29], which enables scalable adaptation to the allocated transmission rates.

In this experiment, users have compressed and encoded video sequences shown in Table I, and transmit the encoded bitstream. A single video file has 1000 s duration, which was obtained by concatenating 100 times of the same typical MPEG test sequences. Users receive the announced quality benefit based on the SIP and decide one of the subnetworks that they join. Once users join the subnetwork, users declare the required information for the resource division using SDP to their QAPs. Then, the QAPs decide TXOPs that can be allocated to each user based on the KSBS and notify the determined TXOPs to users using RTSP. Users having multiple sets of TSPEC select one of the TSPEC parameters that can be fit to the allocated transmission rates, and start to transmit their bitstream. If additional users join a subnetwork, the above process is repeated and new TXOP allocation is allocated to users. Then, users adaptively select another set of TSPEC parameters and transmit their bitstream.

Fig. 4 shows that the derived quality of a particular user transmitting *Mobile* sequences as users switch or join subnetworks. In these experiments, users can transmit their bitstream while they switch or join subnetworks. In Fig. 4(a), the user initially is located in a congested subnetwork, deriving approximately 25.7 dB. The user improves its achieved quality by switching to the other less congested subnetwork, deriving approximately 29 dB (at 90 s). However, as more users switch and join the subnetwork (e.g., at 170, 280, and 380 s), its derived quality decreases. When one of the other users switches to the other subnetwork (e.g., at 460 s), the derived quality of the user increases. Fig. 4(b) shows the derived quality of the user when new users join the subnetwork based on the different resource division policies. As more users join the subnetwork, the derived quality decreases in both policies. Since the ERA simply divides the resources by the number of users in the subnetwork and does not consider the multimedia characteristics, the quality can be derived below the minimum required quality (25 dB in this simulation). However, the KSBS can explicitly consider the multimedia characteristics including the minimum required quality, it can ensure the minimum required quality.

VII. CONCLUSION

In this paper, we have discussed a brokerage-based decentralized resource allocation scheme for multiuser multimedia transmission over networks. Resource brokers deploy two bargaining solutions, which are KSBS and EBS, and explicitly consider the quality impact for different resource division policies. By modeling the proposed admission control scheme as a quality-driven congestion game, we analytically investigated the speed of the convergence and show that n users in the network can reach a PSNE at most $(n-1)$ subnetwork switches. We also quantified the fairness achieved by a PSNE using a newly introduced FCM. We showed that the proposed resource management approach provides a lower value of the FCM (i.e., more fair resource allocation) if users transmit similar video sequences. Moreover, we quantitatively investigated the impact of different quality thresholds of each user on the speed of convergence, and show that higher quality thresholds of the users can lead to a faster convergence. Finally, the results from our real implementation show that our quality-driven approach outperforms existing resource-driven approaches.

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