Auction Based Resource Allocation and Pricing for Heterogeneous User Demands in eMBMS

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***Abstract*—Multicast transmission has been gaining importance as an efficient means of delivering bandwidth hungry video content and is expected to become an integral part of cellular networks worldwide. This has resulted in the need for generalized allocation algorithms that are capable of handling multiple multicast and unicast services with different Quality of Service (QoS) requirements. In this paper, we propose such a Vickrey-Clarke-Groves (VCG) auction based resource allocation and pricing algorithm. The proposed algorithm takes allocation decisions based on the QoS requirements of the end users for maximizing the system social utility. Even though the users in a multicast group are served on the same PRB, requirements of each individual user are taken into consideration while making the allocation decisions. The proposed algorithm ensures that the users report their true valuations of the system resources. VCG auctions provide a general framework for designing truthful optimal mechanisms. However, in many cases, VCG auction turns out to be NP-hard. In this paper, we propose an efficient, polynomial time implementation of the proposed VCG mechanism. Using simulations, we show that the algorithm successfully meets the unique demands of all unicast and multicast services.**

***Index Terms*—VCG mechanism, Multicast, LTE, Resource Allocation, Strategy-proof**

I. Introduction

The immense increase in the amount of multimedia traffic and in the variety of consumer devices in the last decade or so has lead to a paradigm shift in the cellular networks. Video single handedly comprises more than three fourths of the world's data traffic [1]. We have an extremely wide variety of video services, each with it's own unique network requirements. At the user end, we have devices ranging from hand held 5 inch smart phones to ultra high definition home theaters streaming content at all resolutions. This has led to the need for better bandwidth utilization capable of handling an increasingly heterogeneous data traffic. Multicast transmission provides an efficient means of handling these requirements.

Multicast and broadcast functionality of Long Term Evolution (LTE) is referred to as evolved Multimedia Broadcast Multicast Service (eMBMS) [2]. eMBMS allows for multiple evolved NodeBs (eNBs) to transmit the same content over the same frequency in complete synchronization. The area over which the eNBs broadcast the content forms what is known as a Multicast Broadcast Single Frequency Network (MBSFN). While MBSFNs are useful for disseminating important information on a large scale, using eMBMS for providing a variety of content to the User Equipments (UEs) in a cell is a more complex and interesting use case. Multicast using eMBMS is ideal for handling the large video streaming demands of cellular networks. It can transmit content to a large number of UEs over the same Physical Resource Blocks (PRBs) (A PRB is the smallest unit of time frequency resource in LTE [3]). All the UEs subscribed to the same eMBMS service form a single multicast group and are served on the same PRBs. As a result, the UEs in a group could comprise of any number of different devices wanting to stream content at various resolutions depending on factors like device capabilities and data subscription plans.

In the current state of cellular networks, a variety of services would be simultaneously going on in a typical LTE cell. There would be unicast data transmission, Voice over LTE, browsing, file downloads along with multicast streaming. Therefore, resource allocation algorithms specifically designed for multicast transmission have limited practical usability. There is a need for designing generalized allocation algorithms that encompass all types of services, devices and QoS requirements. In this paper, we propose such an algorithm. The proposed algorithm provides a unified mechanism for allocating resources to all kinds of services and devices simultaneously. In addition to this, the algorithm also provides a means to determine the prices to be paid by UEs according to the Quality of Service (QoS) received by them.

A. Related Literature and Contributions

Multicasting has received considerable attention from the research community recently. In this section, we discuss the existing literature relating to resource allocation for multicast transmission. In [4], the authors study optimal pricing for Scalable Video Coding (SVC) multicasting systems with stochastic user arrivals using multi-dimensional MDP. The problem of minimizing the number of PRBs required to meet requirements of each multicast user is consider in [5], [6]. In [7], authors make use of a multi-criteria decision making tool called Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [8] for resource allocation in SVC multicast video streaming. The tool tries to strike a balance between throughput, fairness and user satisfaction. TOPSIS has also been used in [9] for comparing the performance of various multicast resource allocation schemes. In [10], authors propose a genetic algorithm based throughput maximizing resource allocation for OFDMA multicast using the techniques from [11] for power allocation. In [12], authors consider the problem of determining a throughput maximizing resource allocation for an MBSFN area. They propose a joint multicast/unicast allocation scheme that maximizes the total throughput while guaranteeing a certain bit-rate to all the users. In [13], the authors propose a game theoretic bargaining solution for multicast resource allocation in multi-carrier systems like LTE-Advanced (LTE-A).

Auction mechanisms and other game theoretic tools are being increasingly used for addressing various allocation problems in communication networks [4], [14]–[21]. Auctions have also been used in the literature for spectrum allocation [22], channel allocation in vehicular networks [23] and resource allocation in device-to-device multicast [24]. In [14], [15], the authors have proposed a multi-dimensional auction mechanism for crowd-sourced video streaming. Users are assumed to cooperatively share their resources and download various videos for multiple users. In [17], the authors propose an auction based subcarrier allocation for SVC video transmission with the objective of maximizing the net revenue gained by the system. Allocation for SVC video transmission in 4G WiMAX has been dealt with in [18] and [19] using Vickrey-Clarke-Groves (VCG) auction mechanism. In [20], a social utility maximizing mechanism has been proposed for multi-rate multicast over the Internet. It is assumed that the valuations of players are known to each other, but unknown to the central allocating entity.

A common shortcoming in the existing literature is that the channel conditions of the UEs are assumed to be same in all PRBs. This makes the identity of the PRB being allocated to a group irrelevant and the problem reduces to determining the number of resources to be allocated to a group. In practice, however, the channel gain of a UE can be different in each PRB of a sub-frame. This makes the resource allocation problem considerably harder. In this work, we consider the channel variations of UEs over different PRBs in a sub-frame. The current literature also lacks in generalized allocation algorithms that can be effectively used irrespective of the nature of services and allocation objectives. The algorithms in the existing literature are all built around a certain objective function such as maximizing the system throughput [10], [12], ensuring fairness [13], minimizing the PRBs used [6] or maximizing revenue [17]. There is no algorithm that can be used for any objective function and any range of services that might have completely different service requirements.

In practice, the objective of resource allocation may be governed by several different criteria. Also, an eNB will be handling multicast, unicast, some high priority traffic and best effort services all at once. Therefore, in this paper, we propose a generalized resource allocation algorithm that is equipped to handle a combination of multicast and unicast traffic as well as traffics with different priorities and QoS requirements together. We summarize the main contributions below:

- We propose a VCG mechanism for resource allocation in eMBMS. We prove that the mechanism is strategy-proof i.e. it can successfully illicit the true valuations from the UEs. The proposed algorithm is independent of the objective function of allocation. It is suited for use in any scenario and can be used for simultaneous resource allocation to all kinds of traffic.
- We propose a computationally efficient Maximum Weight Bipartite Matching (MWBM) based implementation of the proposed VCG mechanism.
- Through extensive simulations in an LTE environment, we show that the proposed mechanism successfully meets the QoS requirements of all the users.

The rest of the paper is organized as follows. We present the system model and define the problem in Sections II and III, respectively. The VCG mechanism is presented in Section IV. It's MWBM implementation is discussed in Section V and the simulation results in Section VI. Section VII concludes the paper.

II. System Model

The system is comprised of an LTE cell with M UEs and S eMBMS services available that the UEs can subscribe to. UEs either subscribe to one of the eMBMS services or receive unicast content. The UEs subscribed to an eMBMS service form a multicast group that is considered as a single entity for resource allocation. We denote by L the total number of entities inclusive of all unicast UEs and multicast groups. Without loss of generality, we will refer to all the entities as eMBMS groups/services in general, keeping in mind that a unicast UE is simply an eMBMS group containing just one UE. The i^{th} eMBMS group is denoted by G_i, and we use $i(k)$ to denote the index of a group to which UE k belongs. Let $[n] = \{1, \ldots, n\}$. Thus, $[M]$ and $[L]$ denote the set of UEs and the set of eMBMS groups, respectively. Every group has an associated rate of transmission at which the UEs in it need to be served. Let R_i be the rate corresponding to G_i. Resource allocation is done every sub-frame and every group is allocated one PRB in every sub-frame. If the rate achievable by a UE from G_i in the PRB assigned to it's group is greater than or equal to R_i, the content is successfully received by the UE in that sub-frame. Otherwise, the UE is said to have encountered a loss. We assume that data is available for transmission to the groups in every sub-frame.

The channel gains of UEs vary across sub-frames and also across PRBs in a sub-frame. The channel gain of a UE is a function of path loss, shadowing and multipath due to reflections from the surroundings. The eNB is assumed to have full knowledge of the Channel State Information (CSI) and hence the achievable rates of all the UEs in every sub-frame. Since every UE experiences a different channel in different PRBs, the maximum rate achievable by a UE also varies across PRBs. We denote by $r_{kj}[t]$, the maximum rate achievable by UE k in PRB j in sub-frame t. Say UE k belongs to G_i and PRB j is allocated to this group in sub-frame t. Then, data will be transmitted in j at rate R_i and UE k can successfully receive this data only if $r_{kj}[t] \geq R_i$. So, we define the loss encountered by UE k in PRB j in sub-frame t as:

$$\ell_{kj}[t] = \begin{cases} 0, & \text{if } R_i \leq r_{kj}[t], \\ 1, & \text{otherwise.} \end{cases} \tag{1}$$

Every UE in the system has a certain valuation for being scheduled for service in a sub-frame. We use $v_k[t]$ to denote this valuation for UE k in sub-frame t. Note that the valuation captures the resource requirement of a UE which could be a function of any number of factors like the data plan of a UE, the quality of video it requires or the amount of packet loss it has encountered in the past. The valuation of a UE is it's private information and we assume no structure and place no restrictions whatsoever on what the valuations can be. The results and algorithms proposed in this paper are independent of the nature of the UE valuations. In the next section, we discuss the problem formulation.

III. Problem Formulation

In this work, we seek to determine a resource allocation policy for eMBMS that is capable of satisfying the service requirements of a heterogeneous mix of UEs and multicast groups based on their valuations. There are two main challenges in designing such a policy: 1) Since the UE valuations are unkown to the eNB, it has to rely on the reported valuations for making the allocation decisions. Malicious UEs reporting false valuations can bias the policy and hog resources. It is therefore essential that the resource allocation policy successfully illicit the true valuations from the UEs. 2) The second challenge arises due to the existence of multicast groups. The policy has to take allocation decisions based on the valuations of individual UEs but a PRB is allocated to the entire group. However, because of distinct channel conditions of the UEs in a group, only a subset of UEs can be successfully scheduled. The policy should be capable of handling such dynamics.

Before stating the problem formally, we define a few essential terms and notations. Recall that each group is allocated one PRB in a sub-frame. We denote a resource allocation policy by Γ and define an allocation vector of length L, $\mathbf{A^\Gamma[t]}$ that contains the identities of the PRBs allocated to each group by Γ in sub-frame t. For instance, if it's first element $A_1^\Gamma[t] = 2$, it means that PRB 2 has been assigned to G_1 in sub-frame t. Also, $A_i^\Gamma[t] = 0$ indicates that G_i has not been scheduled in sub-frame t. We also define an allocation indicator random variable $x_{ij}^\Gamma[t]$ that indicates whether or not PRB j has been assigned to G_i in sub-frame t under Γ. So,

$$x_{ij}^\Gamma[t] = \begin{cases} 1, & \text{if } \mathbf{A_i^\Gamma[t]} = j, \\ 0, & \text{otherwise.} \end{cases}$$

Definition 1. ***Feasible resource allocation:*** *Resource allocation in a sub-frame is said to be feasible if it assigns at most one PRB to each multicast group such that no two groups are assigned the same PRB. In other words, a feasible resource allocation in sub-frame t corresponds to an allocation vector $\mathbf{A^\Gamma[t]}$ such that no two non-zero elements in it are equal, i.e., if $A_i^\Gamma[t] \neq 0$, then $A_i^\Gamma[t] \neq A_{i'}^\Gamma[t]$ for every $i' \neq i$.*

In this paper, we aim to design auction resource allocation. We assume that each UE k communicates its bid value b_k at the beginning of each sub-frame. The resource allocation in a sub-frame is done at the eNB based on the bids received in the sub-frame. In addition to the resource allocation, eNB also decides on the prices each UE must pay to avail the service. We assume that the users are rational and selfish. Thus, they may report a bid value which is not same as their true valuation if doing so benefits them. These concepts are formalized in the following definitions.

Definition 2. ***Auction based resource allocation policy:*** *An auction based resource allocation policy Γ takes the bids of UEs ($b_k[t]$'s) as input and outputs a feasible allocation and a price to be paid by each UE ($p_k^\Gamma[t]$) in every sub-frame.*

Definition 3. ***Utility of a UE:*** *The utility of UE k in sub-frame t under policy Γ, $u_k^\Gamma[t]$ is defined as the difference between the valuation of the UE and the price $p_k^\Gamma[t]$ it pays for being served in that sub-frame i.e. $u_k^\Gamma[t] = v_k[t] - p_k^\Gamma[t]$. If a UE is not scheduled for reception in sub-frame t, it's utility in that sub-frame is 0.*

Definition 4. ***Social utility:*** *The social utility of the system in sub-frame t under policy Γ, $V^\Gamma[t]$ is defined as the sum of the valuations of the UEs scheduled for service by Γ in that sub-frame. Using the definition of $\ell_{kj}[t]$ and $x_{ij}^\Gamma[t]$, we can write $V^\Gamma[t] = \sum_k v_k[t] \sum_j x_{i(k)j}^\Gamma[t](1 - \ell_{kj}[t])$.*

Equipped with these definitions, we now define the problem addressed in this paper. Let Λ denote the set of all possible resource allocation policies. Our aim is to determine the optimal auction based resource allocation policy $\Gamma^\star \in \Lambda$ that provides a feasible, social utility maximizing resource allocation in every sub-frame. In the next section we propose such a resource allocation policy.

IV. VCG Auction for eMBMS Resource Allocation and Pricing

The VCG auction [25] is a form of sealed bid auction that maximizes the social utility of the system. It takes the bids of buyers as input and allocates items to highest bidders but the price paid by the winning bids is equal to the damage caused by them to the rest of the bidders. We will explicitly state how this 'damage' is calculated later on this section. It is a known result that in VCG mechanism, bidding of the buyers' true valuations is a dominant strategy [26] meaning that the participants have no incentive to not report their true valuations of the items. These features make the VCG mechanism suitable for resource allocation and pricing in an eMBMS network. However, in most cases, implementing a VCG auction turns out to be NP-hard. We now discuss the proposed VCG based allocation mechanism and give a polynomial time implementation for it in Section V.

Since all the allocations and pricing calculations are taking place on a sub-frame basis, we fix a sub-frame t and eliminate it from the notations for the sake of notational simplicity. Consider the PRBs in a sub-frame to be commodities that the UEs want to acquire. The UEs act as bidders who have a certain valuation for acquiring these commodities. Since each group is allotted one PRB in a sub-frame, it follows that each UE can acquire at most 1 PRB. Also, since all the UEs in an eMBMS group are to be served on the same PRB, our system is further bound to allocate the same commodity to all the UEs that belong to the same group. The objective of the VCG mechanism in this case would then be, to determine a feasible allocation in every sub-frame that maximizes the sum of winning bids subject to these allocation constraints.

We now introduce and define a few notations that will be used in the rest of the text. Recall that the valuation of UE k for obtaining a PRB is equal to v_k and the bid submitted by it is denoted by b_k. The VCG mechanism chooses an allocation that maximizes the sum of winning bids, $\sum_k \sum_j b_k x^{\Gamma}_{i(k)j}(1-\ell_{kj})$. Let $\{x^{\Gamma_{-k}}_{ij}\}$ be the allocation indicators under policy Γ in the absence of UE k. Then, the price paid by UE k for service (i.e. the damage caused by it to the other bidders) is:

$$p^{\Gamma}_k = \sum_q \sum_j b_q x^{\Gamma_{-k}}_{i(q)j}(1-\ell_{qj}) - \sum_{q\neq k} \sum_j b_q x^{\Gamma}_{i(q)j}(1-\ell_{qj}).$$

The utility of the UE under this allocation is $u^{\Gamma}_k = v_k - p^{\Gamma}_k$.

The steps involved in the proposed allocation mechanism $\Gamma^\star$ are: 1): The UEs report their bids, b_ks to the eNB. 2): The eNB determines the allocation vector $\mathbf{A^{\Gamma}}$ and the corresponding x^{Γ}_{ij}s that maximize the quantity $\sum_k \sum_j b_k x^{\Gamma}_{i(k)j}(1-\ell_{kj})$ and allocates PRBs accordingly. 3): The price to be paid by UE k, p^{Γ}_k is calculated for every k. These are periodically transmitted to and stored at the Policy and Charging Rules Function (PCRF) for charging purposes.

In the VCG mechanism, there is no incentive for the UE to misrepresent it's valuation since the utility gained by the UE by reporting a false valuation will always be lower or will remain the same. Therefore, the system can allocate resources in an optimal manner without UEs hogging resources by misrepresenting their requirements. This property is referred to as 'strategy-proofness' of the mechanism. It is this property that makes VCG a social utility maximizing mechanism. Since all bidders are forced to bid their true valuations, maximizing the sum of winning bids becomes equivalent to maximizing the system social utility. The strategy-proofness of $\Gamma^\star$ however does not obviously follow from the strategy-proofness of the conventional VCG mechanism due to the nature of resource allocation in multicast. Here, a single commodity is allocated to an entire group of bidders, some of whom may still gain no utility whatsoever. So, the strategy-proofness of $\Gamma^\star$ needs to be explicitly proved. We do this in the following result.

Theorem 1. $\Gamma^\star$ *is strategy-proof.*

Proof. Since we will be dealing with policy $\Gamma^\star$ throughout this proof, we drop Γ from the notations for simplicity e.g., the allocation vector will simply be denoted by $\mathbf{A}$ instead of $\mathbf{A^{\Gamma^\star}}$. Also, as before, we fix a sub-frame and drop the sub-frame indicator t from the notations as well.

Consider a UE k with it's true valuation being v_k. Let B denote the sum of winning bids under $\Gamma^\star$ when all UEs report their true valuations and let $\mathbf{A}$ be the corresponding allocation vector. We use B_{-k} to denote the sum of winning bids in the absence of UE k. Then, the price paid by k if it is scheduled under $\Gamma^\star$ is $p_k = B_{-k} - (B - v_k)$ and it's utility is $u_k = B - B_{-k}$. If k is not scheduled, then $u_k = p_k = 0$. If k reports it's true valuation, it either gets scheduled by $\Gamma^\star$ or it doesn't. We will look at both these cases separately.

***Case 1*:** UE k gets scheduled by reporting $b_k = v_k$ truthfully. Now, let us say that it reports bids b'_k instead. Then, one of the following cases arise:

• $\mathbf{b'_k > v_k}$: If UE k bids a value greater than it's valuation, it should continue to be scheduled. Suppose that this is not the case and k is not scheduled when it bids b'_k. Let B' be the sum of winning bids in this case, the rest of the bids being same as for B. Since $b'_k > v_k$, $b'_k - b_k = \delta > 0$. If allocation vector $\mathbf{A}$ is used in this scenario, k will be scheduled and the resulting sum of winning bids will be $B'' = B' + b'_k > B'$ which is a contradiction since $\Gamma^\star$ maximizes the sum of winning bids. Therefore, UE k will be scheduled when it bids $b'_k > v_k$ resulting in sum of winning bids $B' = B + \delta$. Let us now look at the utility obtained by it.

The price paid by k in this case will be $p'_k = B_{-k} - (B' - b'_k) = p_k$ and it's utility is $u'_k = v_k - (B_{-k} - (B' - b'_k)) = B' - B_{-k} - \delta = B - B_{-k} = u_k$. Therefore, UE k does not gain any utility by reporting b'_k instead of b_k.

• $\mathbf{b'_k < v_k}$ and k does not get scheduled: This is a trivial case since $u'_k = 0 < u_k$ and there is no incentive for k to bid b'_k instead of b_k.

• $\mathbf{b'_k < v_k}$ and k still gets scheduled: Since $b'_k < v_k$, $b_k - b'_k = \delta > 0$. Note that $B' = B - \delta$. Here, $p'_k = B_{-k} - (B' - b'_k) = p_k$ and it's utility is $u'_k = v_k - (B_{-k} - (B' - b'_k)) = B' - B_{-k} + \delta = B - B_{-k} = u_k$. Therefore, UE k has no incentive in bidding b'_k instead of b_k.

***Case 2*:** UE k does not get scheduled by reporting $b_k = v_k$ truthfully. In this case $u_k = 0$. Now, let us say that it bids b'_k instead. One of the following cases arise:

• $\mathbf{b'_k > v_k}$ and k still does not get scheduled: This is a trivial case since $u'_k = 0 = u_k$ and their is no incentive for k in bidding b'_k instead of b_k.

• $\mathbf{b'_k > v_k}$ and k gets scheduled: Since $b'_k > v_k$, $b'_k - b_k = \delta > 0$. Note that $B' - B \leq \delta$. The price paid by k, $p'_k = B_{-k} - (B' - b'_k) = B - (B' - b'_k) \geq b'_k - \delta = v_k$. Therefore, it's utility is $u'_k = v_k - p'_k \leq 0$. Therefore, UE k has no incentive in bidding b'_k instead of b_k even if it does get scheduled.

• $\mathbf{b'_k < v_k}$: If UE k bids a value lower than it's valuation, it should continue not being scheduled. Suppose that this is not the case and k is scheduled when it bids b'_k. Let B' be the sum of winning bids in this case, the rest of the bids being the same as for B. Let $\mathbf{A}'$ be the corresponding allocation vector. Now, if the same allocation vector is used when the UEs bid their true valuations, the resulting sum of winning bids will be $B'' = B + v_k$ which is a contradiction since B is the maximum bid value obtainable with true valuations. Thus, it is not possible for k to get scheduled when it bids b'_k. Therefore, there is no incentive in bidding b'_k instead of b_k.

We have shown for all possible cases that manipulating the actual valuations in any manner does not result in any utility gain for the UEs under allocation policy $\Gamma^\star$. This proves that $\Gamma^\star$ is strategy-proof. □

A. Computational Complexity

Using brute force to implement $\Gamma^\star$ requires going through all possible resource allocations and calculating the sum of winning bids for each allocation. The optimal allocation can then be obtained by choosing the one that maximizes the sum of winning bids. The computational complexity of this algorithm turns out to be $\mathcal{O}(L\binom{N}{L}L!)$. This is computationally very expensive and unsuitable for practical implementation. Therefore, in the next section, we present a computationally efficient Maximum Weight Bipartite Matching (MWBM) based implementation of $\Gamma^\star$.

V. MWBM Allocation for eMBMS

We propose a MWBM implementation of $\Gamma^\star$ that has a computational complexity of $\mathcal{O}(L^2N)$. The VCG mechanism of $\Gamma^\star$ can thus be implemented in polynomial time using this matching. We first construct the bipartite graph for the matching and then prove that determining a maximum weight matching for it is equivalent to determining a resource allocation according to $\Gamma^\star$. Construct a bipartite graph $\mathcal{G} = (U, V, E)$ where U is the set of eMBMS groups $[L]$ and V is the set of PRBs $[N]$ as shown in Fig. 1. Since the MWBM is carried out every sub-frame, we fix a sub-frame and eliminate t from the notations. The weight of the edge between vertex $i \in U$ and vertex $j \in V$ is defined as $w_i^j = \sum_{k \in G_i} b_k \times (1 - \ell_{kj})$. The MWBM of $\mathcal{G}$ is the social utility maximizing resource allocation given by $\Gamma^\star$. We prove this in the following result.

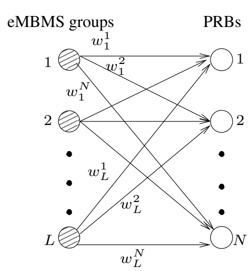

Fig. 1: Bipartite graph between multicast groups and PRBs

Lemma 1. *MWBM for graph $\mathcal{G}$ results in the same allocation as that given by $\Gamma^\star$.*

Proof. Let us first establish that the MWBM of $\mathcal{G}$ results in a feasible resource allocation. By definition of a matching, the MWBM of $\mathcal{G}$ selects edges with no common vertices. Therefore, a vertex from U is matched to at most one vertex from V and vice-versa. This means that each group is given a single PRB in a sub-frame. It also ensures that, in the resulting allocation vector $\mathbf{A}[\mathbf{t}]$, $A_i[t] \neq A_{i'}[t] \ \forall \ \{i, i' \in U\}$. Hence, by Definition 1, the resulting resource allocation is feasible. All that is left to show is that this feasible allocation also maximizes the sum of winning bids.

Since MWBM searches for a maximum weight matching with no common nodes, it effectively maximizes the quantity $\sum_{i,j} w_i^j x_{ij}^\Gamma = \sum_j \sum_i \sum_{k \in G_i} b_k (1 - \ell_{kj}) x_{i(k)j}^\Gamma = \sum_j \sum_k b_k x_{i(k)j}^\Gamma (1 - \ell_{kj})$ which is the quantity being maximized by $\Gamma^\star$. Thus, MWBM for $\mathcal{G}$ successfully implements the allocation mechanism of $\Gamma^\star$. □

VI. Simulations

In order to study the performance of the proposed allocation algorithm, we have carried out simulations in an LTE environment. We first discuss the simulation setup and then present the results. We consider an LTE cell with 100 UEs distributed uniformly at random. The channel models used are in accordance with the 3GPP specifications [27]. There are 5 different eMBMS streams available for subscription and all UEs in the cell are either subscribed to one of them or require some unicast service. We run the simulations for 10^5 sub-frames. Other relevant simulation details are given in Table I.

For the purpose of these simulations, we assume that each UE has a certain packet loss requirement that needs to be met. The loss tolerable by a UE could be a function of factors like the streaming quality required by it or the kind of service it has subscribed to. This requirement is known to the UEs alone. The valuation of the UEs in a sub-frame is some function of their loss tolerance and the loss they have encountered up to that time. The UEs report their respective valuations to the eNB in the form of bids. The eNB then allocates a PRB to each eMBMS group using the algorithm detailed in Section V. We have compared the performance of our policy with a throughput maximizing greedy policy Γ^G.

Fig. 2 shows the plot of the loss tolerance of UEs and the actual loss encountered by them under $\Gamma^\star$ and Γ^G. We observe that the loss encountered by the UEs under $\Gamma^\star$ is within the tolerable loss for every UE. The loss under Γ^G exceeds the loss tolerance of many UEs in the system. The key takeaway from this plot is that $\Gamma^\star$ succeeds in meeting the loss requirements of all the UEs even though their tolerable losses are not known to the eNB. The eNB makes the allocation decisions based solely on the bids submitted by the UEs.

In the loss tolerant system under consideration here, the pattern in which losses occur is also important for the quality of video streaming services. For a smoother user experience, the losses should be spread uniformly over time. In order to see how the loss patterns evolves over time, we look at the average percent packet loss under the two policies as a function of time. This is shown in Fig. 3. We can make two main observations from the figure. Firstly, $\Gamma^\star$ results in a significantly lower average loss than Γ^G. Secondly, we observe that the loss pattern of the proposed mechanism is smoother than that of Γ^G, indicating that the losses are more uniformly spread under our policy.

VII. Conclusions

In this paper, we have addressed the problem of resource allocation for heterogeneous UE demands encompassing unicast and multicast services in LTE. We have considered a scenario where the multicast group members and unicast users have different QoS expectations and hence different valuations for being scheduled. We have proposed a strategy-proof VCG mechanism that takes allocation decisions based

TABLE I: System Simulation parameters [27]

Parameters	Values
System bandwidth	20 MHz
Path loss model	L = 128.1+37.6 $\log 10(d)$, d in kilometers
Shadowing	Log Normal with 10 dB standard deviation
White noise power density	-174 dBm/Hz
eNB noise figure	5 dB
eNB transmit power	46 dBm

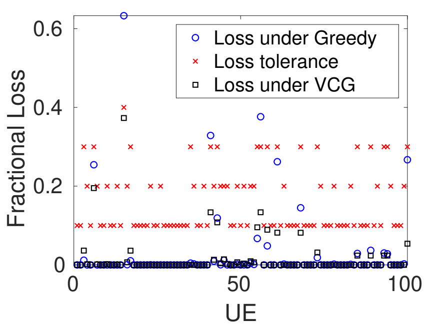

Fig. 2: Tolerable loss versus loss encountered

on the reported UE valuations. The mechanism succeeds in meeting the QoS requirements of the UEs in all the eMBMS groups. We have also proposed a polynomial time MWBM implementation of our mechanism that is efficient and inexpensive to implement. We have also demonstrated it's effectiveness through simulations.

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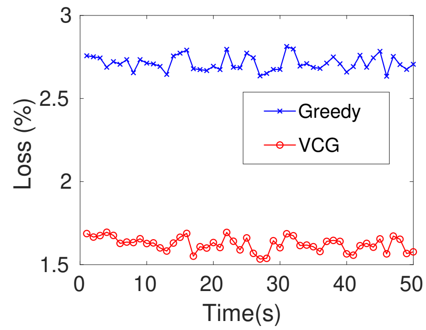

Fig. 3: Average loss pattern over time

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