Network-Centric User Assignment in the Next Generation Mobile Networks

Luan Huang, Yajian Liu, *Student Member, IEEE*, Shyamalie Thilakawardana, and Rahim Tafazolli, *Member, IEEE*

Abstract—This letter addresses the user assignment problem for multimedia streaming applications in heterogeneous multicast-enabled wireless networks using a network-centric strategy. The optimal problem is mathematically formulated and proven to be Non-deterministic Polynomial-time (NP)-hard. An efficient heuristic algorithm is then proposed to find sub-optimal solutions in practical systems. Simulation results demonstrate the improved performance of this heuristic in comparison to a conventional user-centric algorithm.

Index Terms—User assignment, multicast, multimedia.

I. INTRODUCTION

ONE of the important applications envisioned in the next generation mobile systems is to provide efficient multimedia streaming services (unicast or multicast-based) over heterogeneous wireless networks. One principle research challenge foreseen in this context is to assign a user to the best access network when he/she is reachable throughout a wide variety of networks [1], [2], [3], [4]. The widely used solution in recent literature is the user-centric (UC) approach in which every mobile user chooses the access network based on the knowledge obtainable at user side such as, the perceived quality of received services etc [1], [2], [3]. In [4], a user assignment algorithm with network assistance was proposed. However, the existing mechanisms may lead to inefficient resource utilization due to the limited inputs used in the user assignment process. In particular for multicast-based services, the one-to-many transmission characteristic makes this situation worse due to the increased heterogeneity of users interested in the same content. This letter addresses the User Assignment (UA) problem using a network-centric approach in which total resources are coordinated among all users by the network operator so as to optimize the usage of overall resources. Moreover, we exploit the rate-adaptive feature of multimedia applications [5] to further improve the efficiency of wireless resource utilization. We present a formal definition and formulation of the UA problem, using a mathematical optimization technique, which we have not yet found in literature.

II. PROBLEM DEFINITION

To be rate adaptive, each multimedia content is encoded with a set of discrete bit rates. A user can only be served with

a rate supported by both his/her terminal and the network. We adopt the concept of *utility*, which is widely used for the radio resource optimization [6]. Each user has a utility function that quantifies the benefit of usage of certain resources. As in [6], the utility function $\mu(r)$ is a non decreasing function of the data transmission rate r . In particular, when $\mu(r) = r$, the utility is the throughput, which is the objective of most traditional mobile network optimizations. The objective of the UA problem is to maximize the aggregated utilities among all the users in the system. This objective is achieved by selecting the best combination of cells and the transmission rates to deliver required contents to interested users simultaneously.

Let C be the set of multimedia contents to be delivered in the system. Each $c \in C$ has a set of supportable rates S_c . Let H be the set of multicast-enabled cells in the system. Each cell $h \in H$ can be characterized by a two-dimensional vector (m_h, n_h) , where m_h denotes the maximum available bandwidth in the cell (in, e.g. kbps), and n_h represents the type of the network to which the cell belongs (e.g., 3G or broadcasting network). Let U be the set of users in the system. Each user $u \in U$ can be specified by a four-dimensional vector $(O_u, g_u, k_u, \mu_u(d_u))$, where $O_u \subseteq H$ is the candidate cell set of the user based on his/her geographic location and the terminal's supportable air interfaces; g_u denotes the ID of the content requested by the user; k_u represents the capacity of the user's terminal, in terms of the maximum supportable transmission rate and $\mu_u(d_u)$ is the utility of the user with the actual received rate d_u . If d_u is not available, $\mu_u(d_u) = 0$. d_u should be chosen from the supportable data rates of the user's desired content g_u , subject to the user's terminal capacity limit k_u . Therefore, for each user u , there is a particular set of transmission rates R_u feasible to choose. R_u contains all the rates not greater than k_u in set S_{g_u} . Hence, the user's utility can be interpreted as $\mu_u(r)$, $r \in R_u$. In addition, the serving cell's capacity limit is another factor that determines r . We let $w_{u,h,r}$ be the consumed radio resources of user u given the serving cell h and transmission rate r . $w_{u,h,r}$ is interpreted as the consumed bandwidth (in kbps) in our work. For unicast, $w_{u,h,r}$ can be calculated straight forward from his/her allocated rate r once the assignment for this user is completed, i.e., $w_{u,h,r} = r$. In contrast, radio resources can be used more efficiently in multicast by delivering only one copy of content (via a multicast radio channel) to a group of users in a cell. Hence, the average consumed resource of an individual user is negative proportional to the number of users assigned in the same radio transmission in cell h (we denote this number as M_h), and thus, the consumed resource is unknown until all the users have been assigned. Mathematically, $w_{u,h,r} = \frac{r}{M_h}$,

Manuscript received July 12, 2006. The associate editor coordinating the review of this letter and approving it for publication was Prof. Tracey Ho. This work was supported in part by the Core 3 Research Programme of Mobile VCE.

The authors are with the Center for Communication Systems Research (CCSR), University of Surrey, Guildford, Surrey, U.K. GU2 7XH (email: {l.huang, y.liu, s.thilakawardana, r.tafazolli}@surrey.ac.uk}).

Digital Object Identifier 10.1109/LCOMM.2006.061086.

Fig. 1. An example of UA problem.

if $M_h > 0$.

The UA optimization is to assign each user from U to exactly one cell from O_u , and serve this user with exactly one transmission rate from R_u , so as to maximize the total user utilities. Furthermore, each user interested in the same content can be assigned to a different cell and served with different data rate, as long as the capacity m of that particular cell is not violated. In a cell, these users are served with one multicast transmission. For instance, in Fig. 1, u_1 and u_2 are interested in content c_1 . $O_{u1} = \{h_3\}$ due to the limits of the 3G cell coverage, and $R_{u1} = \{128, 256\}$ due to the limits of the terminal capacity. As a result, u_1 can be assigned to h_3 with the rate of 128 kbps due to the cell capacity limits. For u_2 , $O_{u2} = \{h_1, h_3\}$, $R_{u2} = \{128, 256, 384\}$. For more efficient resource utilization, u_2 can be given the same assignment as u_1 , thus both of them sharing a common multicast transmission. This assignment can be fulfilled by applying the criterion that assign the user to the cell that consumes the least radio resources, i.e., $w_{u2,h1,128} = 128\text{kbps}$ while $w_{u2,h3,128} = 64\text{kbps}$.

The inputs to the optimization are C , H and U . The output is a binary optimal allocation vector, $x_{u,h,r}$, $u \in U$, $h \in O_u$, $r \in R_u$. If $x_{u,h,r} = 1$, user u is assigned to cell h with rate r . The UA problem can be formally stated as follows:

Maximize:

$$\text{SystemUtility} = \sum_{u \in U} \sum_{h \in O_u} \sum_{r \in R_u} \mu(r) x_{u,h,r} \quad (1)$$

Subject to: Constraint (a) the limits of cell capacity are satisfied, i.e., $\sum_{u \in U} \sum_{r \in R_u} w_{u,h,r} x_{u,h,r} \leq m_h, \forall h \in O_u$; Constraint (b) each user can be assigned to at most one cell, i.e., $\sum_{h \in O_u} x_{u,h,r} \leq 1, \forall u \in U, r \in R_u$; Constraint (c) a user can only be given at most one rate from R_u at a time, i.e., $\sum_{r \in R_u} x_{u,h,r} \leq 1, \forall u \in U, h \in O_u$. Constraint (d) the output is a binary integer, i.e., $x_{u,h,r} \in \{0, 1\}, \forall u \in U, h \in O_u, r \in R_u$.

We prove the UA problem to be NP-hard by reducing it to a standard NP-hard problem i.e. Generalized Assignment Problem (GAP) [8]. The GAP is stated: given I knapsacks, J items, with p_{ij} and a_{ij} the profit and weight of item j respectively, if assigned to knapsack i , and b_i the capacity of knapsack i , the problem is to assign each item to exactly one knapsack so as to maximize the total profit assigned without assigning to any knapsack where a total weight greater than its capacity. Any instance of GAP is equivalent to the instance of UA obtained by mapping the user and cell to be the item and knapsack in the GAP respectively; assuming only one rate included in R_u ; setting user utility $\mu_u(r) = p_{ij}$; user resource

$w_{u,h,r} = a_{ij}$ and the cell capacity $m_h = b_i$, for $u \in U$, $h \in H$, $c \in C$.

III. ALGORITHM

Due to the NP-hardness of the UA problem, the time required to find its optimal solution increases exponentially with the size of the problem. This prohibitive processing complexity is intolerable in practical systems. In this paper, a computationally efficient heuristic algorithm is instead proposed to find the sub-optimal solutions in practical systems. This algorithm is named Maximize-Utility (MU) heuristic algorithm and takes the following steps.

Step 1: For each unassigned content c , calculate its maximum utility u_max_c . It is defined as the aggregate user utilities assuming these users are given the best assignment. u_max_c is calculated as follows;

a) For each unassigned user for content c , find particular cell(s) from set O_u and the respective transmission rate(s) from set R_u so as to maximize the user's utility while subject to the cell capacity constraint. If there is no feasible cell available, this user is marked as a Blocked-User (BU). If only one cell is feasible, this cell is chosen as the serving cell with the respective transmission rate. The user is marked as an Admitted-User (AU). If there are multiple feasible cells giving the same utility, the user is marked as a Undetermined-User (UU) and is left for future processing along with other UU users. Note that AU users need to be processed prior to UU users, as UU users have more access cells to select;

b) After all users are considered, we determine the serving cell for UU users. The idea is to assign a user to the cell that consumes the least ratio resources [4]. We extend [4] by considering multicast applications. As explained in section II, in multicast, the user resource consumption is unknown until all users are assigned to appropriate cells. We devise (2) to predict the multicast resource consumption RC of a user:

$$RC(u, h, r, c) = \begin{cases} 0 & \text{if a user has been assigned} \\ r/M & \text{otherwise} \end{cases} \quad (2)$$

Where, M is the number of unassigned UU users who can be serviced by the content c in cell h with rate r . This equation indicates that due to the resource sharing among users in a multicast channel in a cell, more users are in this cell, fewer resources are consumed by individual users. Moreover, no extra resource is required for a new user if a user has been assigned to this cell during previous steps. The UU user is then marked as AU.

c) After all users are processed, we calculate the content utility u_max_c based on the assignment calculated during previous steps;

Step 2: Among all the unassigned contents, the one that generates the largest nonzero u_max_c will be distributed to subscribed users throughout cells with rates chosen in step 1;

Step 3: Once the content is assigned, the remaining resource of each chosen cell is updated. Repeat step 1 to step 3 until all the contents have been processed.

TABLE I
NETWORK PARAMETER

	Number of networks (n_1, n_2)	Maximum capacity (kbps/cell)(n_1, n_2)	Number of cells (n_1, n_2)
ND_Case 1	(1,1)	(1024,2048)	(7,1)
ND_Case 2	(5,5)	(1024,2048)	(7,1)

Fig. 2. Overall user utility and user loss probability vs. number of contents under two ND cases ($\mu(r) = r$).

IV. PERFORMANCE EVALUATION

We evaluated our algorithm using OPNET. Two types of key-multicast-enabled networks are considered, i.e., MBMS 3G network n_1 and DVB network n_2 . These networks are overlapping in a common service area A . We study two Network Deployment (ND) cases as presented in Table 1. The capacity limits of each cell are randomly generated. The rate of the content is randomly generated from the vector $\{32, 64, 128, 256, 384\}$ kbps. Users are uniformly distributed over the area A with terminal capacity limits up to 384 kbps. The probability of a user's request for a content follows Zipf distribution [7]. The average number of users for a content is 10 in a cell of type n_1 . We evaluate the MU heuristic algorithm by comparing it to a conventional UC algorithm in which each user chooses a combination of the network and data rate, which gives the highest utility or marginal utility (the difference between the user utility and the monetary cost) [1], [2], [3]. The monetary cost is not considered in our study. In case of the same utility, selection is performed

randomly. Simulation results in Fig. 2 show the MU algorithm achieves significant gain over the UC algorithm in both user utility and loss probability. Furthermore, when the number of contents increases from 10 to 50, or the number of constituent access networks increases from ND_Case 1 to ND_Case 2, more improvement is achieved by the MU algorithm. These results demonstrate the significance and value of using the MU heuristic algorithm for operators to optimize the multicast content delivering in heterogeneous wireless networks.

V. CONCLUSIONS

We presented a network-centric solution to the user assignment problem in multicast-enabled heterogeneous wireless networks. This problem was mathematically formulated and proven to be NP-hard. Moreover, an efficient heuristic algorithm was derived to find the sub-optimal solutions of the problem in practical systems. Simulation results demonstrated the improved performance of this algorithm. Additionally, the proposed algorithm performed consistently well under a wide variety of traffic loads and number of networks. The implementation issues of the proposed algorithm are addressed in [9] in terms of architecture, functional entities, network interfaces, signaling and exchanged parameters. The proposed algorithm is applicable to both off-line and on-line UA problem. For an on-line operation, "batching" of user requests should be performed for individual contents prior to the user assignment in order to aggregate enough users for multicast transmission. The combination of batching and user assignment algorithms can be found in our previous work [10].

REFERENCES

- [1] V. Gazis, N. Houssos, N. Alonistioti, and L. Merakos, "On the complexity of "always best connected" in 4G mobile networks," in *Proc. IEEE VTC 2003*.
- [2] J. Noonan, P. Perry, and J. Murphy, "Client controlled network selection," in *Proc. Fifth IEEE International Conference on 3G Mobile Communication Technologies 2004*.
- [3] O. Ormond, J. Murphy, and G. M. Muntean, "Utility-based intelligent network selection in beyond 3G systems," in *Proc. IEEE International Conferences on Communications (ICC 2006)*.
- [4] G. Fodor, A. Furuskar, J. Lundsjo, "On access selection techniques in always best connected networks," *16th ITC Specialist Seminar*, Aug./Sept. 2004.
- [5] L. Huang and C.-C. Jay Kuo, "Adaptive resource allocation for multimedia QoS management in wireless networks," *IEEE Trans. Veh. Technol.*, vol. 53, no. 2, pp. 547-558, Mar. 2004.
- [6] G. Song and Y. Li, "Cross-layer optimization for OFDM wireless network—part I: theoretical framework," *IEEE Trans. Wireless Commun.*, vol. 4, no. 2, pp. 614-624, Mar. 2005.
- [7] Y. S. Chen, "Mathematical modeling of empirical laws in computer applications: a case study," *Comp. Math. Applicat.*, pp. 77-87, Oct. 1992.
- [8] S. Martello and P. Toth, *Knapsack Problems: Algorithms and Computer Implementations*. Wiley, 1990.
- [9] L. Huang, "Multicast resource management for cooperative mobile and broadcasting networks," *MVCE Core 3, D-IoN-2.2*, Nov. 2005.
- [10] L. Huang, K. A. Chew, and R. Tafazolli, "Efficient multimedia content delivery over cooperative 3G and broadcasting networks," in *Proc. 16th IEEE PIMRC 2005*.