Bandwidth allocation in heterogeneous networks environment from users' perspective

Chaitanya Pande
Electrical department
Indian Institute of Technology, Bombay
Mumbai
Email: chaitanyap@ee.iitb.ac.in

Pritesh Nandgaonkar
Electrical department
Indian Institute of Technology, Bombay
Mumbai
Email: homer@thesimpsons.com

Mustafa H.D.
Electrical department
Indian Institute of Technology, Bombay
Mumbai
Email: homer@thesimpsons.com

S.N.Merchant
Electrical department
Indian Institute of Technology, Bombay
Mumbai
Email: merchant@ee.iitb.ac.in

***Abstract*—With the evolution of mobile terminals and different wireless technologies, there is now a growing emphasis on integration of heterogeneous networks and being able to use multiple networks simultaneously. This need for integration is driven by the inability of the networks to satisfy the ever-increasing users requirements individually. So users would want to use multiple networks simultaneously to fulfill their bandwidth requirements.**

A natural question arises on how to distribute the bandwidth requirement of the users among the available networks. This distribution will depend on multiple criteria associated with networks. We formulate an optimization problem to find the solution for this multi-criteria resource allocation problem for single user, with the aid of Utility Theory. As a natural extension, we also studied multi-user scenario and formulate and solve the multi-objective optimization problem using goal attainment technique.

I. Introduction

With easy availability of communication devices like smart mobile phones, laptops, tablets etc., there has been a huge surge in populace connecting to internet. This requirement is expected to increase with introduction of concepts like Internet of Things(IoT), cloud communication, etc. This will put a huge burden on the different radio access technologies(RATs) to support the bandwidth requirements. Though there has been development of concepts like MIMO, cognitive radio etc., that improved spatial diversity gain, efficient spectrum utilization and increased QoS, the gap between users' bandwidth demands and availability is significant and is expected to increase.

It is not difficult to foresee that communication devices of next generation will have multiple radio interfaces and will be able to connect to multiple networks simultaneously; however, not much effort is directed towards using multiple RATs simultaneously. To support this problem, consider a scenario - A user is running several applications that have bandwidth requirement of 500 kb/s, but the available networks, Wifi and WiMax, have available bandwidth as 300 kb/s and 350 kb/s respectively. So individually, networks will not be able to fulfill user's requirement. However, it is easy to see that if the networks decide to cooperate, they will collaboratively be able to satisfy user's requirement.

A lot of work has been done to solve the issue of best network selection in heterogeneous network scenario. Wang et. al. studied and presented an overview of different mathematical models and approaches to select best network among available networks [1]. They discussed the different tools used to solve this problem like utility theory, MADM, combinatorial optimization, game theory, etc. However, none of them approached the problem from simultaneous use of multiple RATs. In their work by Mustafa et.al.[2], they presented a new paradigm of cooperative communication in which multiple RATs can cooperatively fulfill the ever increasing bandwidth demands of users, with emphasis on energy efficiency. They emphasized the need of a decision function to split the bandwidth requirement of user among available RATs. They also emphasized on the need of a control plane, which is similar to an entity known as Common Radio Resource Management(CRRM) in previous works. The concept of CRRM was introduced by Tolli et. al.[3], who also showed the performance improvement when it is incorporated in a heterogeneous network environment.

In this paper, we investigate the problem of finding a decision function that allocates the bandwidth requirement of a user among the available RATs. We assume that the communication device has multiple radio interfaces and can connect to and communicate using multiple RATs. We also investigate the multi-user version of this scenario, wherein multiple users are competing for available bandwidth of RATs.

II. System Model

We refer to the system model used by Kosmides et. al. [4].

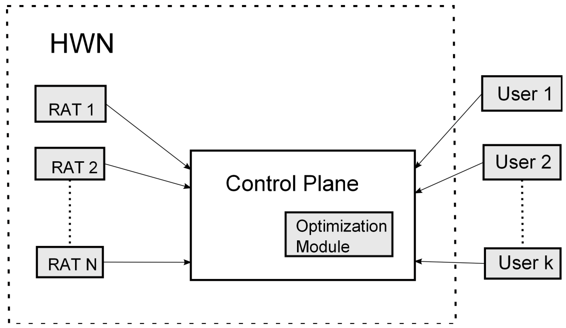

Fig. 1. System Model

In this model, each RAT informs control plane about the bandwidth that it can provide to the users, referred as $b_i,\ i \in \{1, 2, ..., N\}$ for i^{th} network. Every user also informs control plane about its utility functions for various criteria and its bandwidth requirement. Let bandwidth requirement for i^{th} user be $M_i,\ i \in \{1, 2, ..., k\}$ and utility functions be $f_{ij},\ i \in \{1, 2, ..., k\},\ j \in \{1, 2, ..., r\}$ where r are the number of criteria based on which a decision is to be made. control plane solves the optimization problem and informs the users about their respective allocation vectors.

III. Optimization problem

A. Single user

- $c = (c_1, c_2, ..., c_r)$ - criteria set - A set of network criteria based on which a decision is to be made
- $\alpha = (\alpha_1, \alpha_2, ..., \alpha_n),\ \alpha_i \in [0, 1]\ \forall\ i \in \{1, ..., N\}$ - allocation vector
- M_0 - bandwidth requirement of the user

Thus, bandwidth allocated to i^{th} network is $\alpha_i M_0$.
The optimization problem for the single user becomes -

$$\max\ U \tag{1}$$

$$\text{subject to} \sum_{i}^{n} \alpha_i = 1 \tag{2}$$

$$\alpha_i M_0 \leq b_i\ \forall\ i \in \{1, 2, ..., n\} \tag{3}$$

where $U = \prod_{i=1}^{r} [U_i]^{w_i}$ is the total utility obtained from all the criteria(w_i is the relative weight assigned to i^{th} criterion, $\sum_{i=1}^{r} w_i = 1$). This way of aggregating utility functions to evaluate multi-criteria utility is suggested by Nguyen-Vuong et. al [5].

Intuitively, by this formulation of optimization problem, we're interested in an allocation which will maximize user's utility. Constraint (2) suggest that the bandwidth requirement of the user is fulfilled. Constraint (3) suggest that the bandwidth allocated to a network can't exceed the bandwidth that the network is able to provide.

B. Multi-user

For k users, the optimization problem becomes -

$$\max_{\alpha \in [0,1]} U_i\ \forall\ i \in \{1, ..., k\}$$

$$\sum_{j=1}^{n} \alpha_{ij} = 1\ \forall\ i \in \{1, ..., k\}$$

$$\sum_{i=1}^{k} \alpha_{ij} \leq b_j\ \forall\ j \in \{1, ..., N\}$$

where $U_i = \prod_{j=1}^{r} U_{ij}$ is the total utility for i^{th} user. The optimizer for the above problem gives an allocation matrix where i^{th} row correspond to allocation for i^{th} user.

C. Utility Theory

In microeconomics, utility refers to amount of satisfaction obtained by consumption of a good or service. Utility function maps from a value of a good/service to the utility obtained by it. Depending on users' preferences, same value of a good/service may give different utility to different users. For single criterion decision making problems, it is fairly straightforward to directly use the utility and make a decision. For multi-criteria decision problems, the utility of different parameters can be combined together by some mathematical operation, also incorporating the relative preferences of the different parameters for a user, and a decision can be made.

One might argue why to use utility functions at all. One could instead formulate an optimization problem to minimize power or formulate a multi-objective problem to minimize power and cost. However, solution for such a formulation may not give user the same utility as a formulation of above form. So an optimization problem maximizing utility makes more sense.

Nguyen-Vuong et. al. studied the different utility functions for single criterion and aggregate utility function forms in the context of wireless network selection and came up with conditions suitable for an ideal utility function. They proposed that a utility function of the following form satisfies all the the discussed conditions [5] -

$$u(x) = \begin{cases} 0 & x < x_\alpha \\ \frac{\left(\frac{x - x_\alpha}{x_m - x_\alpha}\right)\zeta}{1 + \left(\frac{x - x_\alpha}{x_m - x_\alpha}\right)\zeta} & x_\alpha \leq x \leq x_m \\ 1 - \frac{\left(\frac{x_\beta - x}{x_\beta - x_m}\right)\gamma}{1 + \left(\frac{x_\beta - x}{x_\beta - x_m}\right)\gamma} & x_m < x \leq x_\beta \\ 1 & x > x_\beta \end{cases}$$

where

$$\gamma = \frac{\zeta(x_\beta - x_m)}{x_m - x_\alpha}$$

$$\text{and}\ \ \zeta \geq \max\{\frac{2(x_m - x_\alpha)}{x_\beta - x_m}, 2\}$$

ζ and γ are the tuned steepness parameters.

They also proposed that a suitable aggregation for multi-criteria utility function is formulated as

$$U(x) = \prod_{i=1}^{n} [u_i(x_i)]^{w_i} \tag{4}$$

where n is the number of criteria, w_i is the weight vector for criterion i($\sum_{i=1}^{n} w_i = 1$) and $u_i(x_i)$ is the elementary utility of criterion i that follows the utility form mentioned above.

D. Multi-objective optimization

A basic multi-objective optimization problem is mathematically described as

$$min[f_1(x), f_2(x), ..., f_n(x)]$$
$$x \in S$$

where n $>$ 1 and S represents set of feasible points.

The concept of optimality do not directly apply in the context of multi-objective optimization. Here, the concept of pareto-optimality is used. A feasible point x* is said to be pareto-optimal if for no $x \in S$, all the objective functions improve over x*. So for the above problem, pareto-optimality is as follows -

- Weak pareto-optimality - $\nexists x \in S$ such that $f_i(x) < f_i(x^*)\ \forall\ i \in \{1, 2, ..., n\}$
- Strong pareto-optimality - $f(x^*) \leq f(x)\ \forall\ x \in S$ and $\forall\ i \in 1\{1, ..., n\}$ with strict inequality for atleast one i.

The image of all pareto-optimal points under $F = [f_1(x), f_2(x), ..., f_n(x)]$ is called pareto-curve or pareto-front. The points on pareto-front are also called non-inferior or non-dominated points.

Most of the times, we're interested not in pareto-front but a particular optimizer for the problem. Hence, there is a need of decision maker(DM) who provide subjective performance preferences to choose the best solution among the set of pareto-points. A basic categorization is made of the techniques for solving multi-objective problems based on the instant at which DM is required to provide preference information -

- Prior to the search (a-priori approaches)
- During the search (interactive approaches)
- After the search (a-posteriori approaches)

Of the several techniques available to solve these problems, we used goal attainment for our scenario because the quantities needed to characterize this technique have a simple intuitive interpretation in our scenario. Goal attainment is an a-priori approach in which DM's preferences are available before the search begins. Mathematically, for the above problem, the goal attainment gives the following optimization problem -

$$min\ \alpha$$
$$\text{subject to } f_i(x) - \alpha w_i \leq z_i^{ref}\ \forall\ i \in \{1, 2, ..., k\}$$
$$\sum_{i=1}^{k} |w_i| = 1$$
$$x \in S$$

It has been shown [6] that an optimizer for the above problem gives a pareto-optimal solution.

To characterize our multi-objective optimization problem using goal attainment technique, we need to define goal vector, $z^{ref} \in \mathbb{R}^k$ and weight vector, $w \in \mathbb{R}^k$.

- **w** - w reflects the relative amount by which under- or over-attainment of the desired goals is allowed. It gives an indication of the priority order of the objective functions. In our case, as all the users are of equal priority, $w = [1/k, ..., 1/k]^T$, where k = number of users, k $>$ 1.
- **z**^{ref} - z^{ref} is the goal vector that we want the objective functions to achieve. In our case, goal vector is the maximum value of the utility of a user when it is not competing with any other user i.e. when the full bandwidths of all the networks are available to it.

E. Simulation and results

For simulation, we consider a heterogeneous network scenario consisting of WiMax(IEEE 802.16 $-$ 2004 version), Wifi(IEEE 802.11g) and GSM as the available RATs. The criteria set for the allocation problem is $\mathbf{c} = \{$Power, Cost$\}$.

To calculate power at the allocated bandwidth, we refereed to the power model of [7] (for WiMax and Wifi) and [8] (for GSM)-

$$P_{Wifi} = 4.652 + 0.024f\ W \tag{5}$$
$$P_{GSM} = 0.024 + 11.9f\ W \tag{6}$$
$$P_{WiMax} = 16 + 0.174f\ W \tag{7}$$
$$P_{Total} = P_{Wifi} + P_{GSM} + P_{WiMax} \tag{8}$$

where f is allocated bandwidth in Mb/s. This model is only for the transmission power when adaptive modulation scheme is used, and the datagram is of size 1280 bytes.

To calculate cost at the allocated bandwidth, we assumed a linear model of cost vs bandwidth with different slopes for different RATs. Specifically, for simulations, we used the cost/bandwidth of {WiMax, Wifi, GSM} as {2,1,3}.

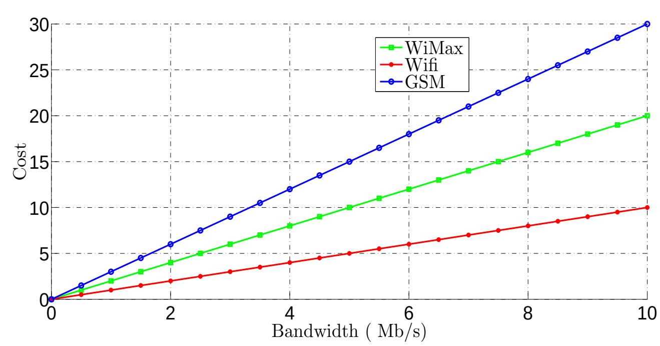

Fig. 2. Cost vs bandwidth

Total cost is given by -

$$c_{Total} = c_{WiMax} + c_{Wifi} + c_{GSM} \tag{9}$$

1) Single user case:

- RATs, **N** = {WiMax, Wifi, GSM}
- Available bandwidths of networks, **b** = {500, 500, 500} Kb/s ({0.488, 0.488, 0.488} Mb/s)
- Relative weights, **w** - It refers to the relative importance of different parameters in the multi-criteria problem(not to be confused with **w** of goal attainment). In their work by Song et. al. [9], they demonstrated the use of Analytic Hierarchy Process(AHP) to determine the relative weights of different criterion. However, for the sake of simplicity, we did not use AHP and instead choose to assign equal priority to power and cost $\implies$ $\mathbf{w} = \{1/2, 1/2\}$

Utility function is characterized by specifying $(x_\alpha, x_\beta, x_m, \zeta)$. The parameters for utility function are described in the following table -

Parameters	Cost utility	Power utility
x_α	0	0
x_β	5	18
x_m	2	10
ζ	2	2

TABLE I. PARAMETERS CHARACTERIZING UTILITY FUNCTION FOR USER 1

The parameters are chosen considering the entire range of power consumption and total cost for range of bandwidth requirement from 300 - 1500 Kb/s, and don't necessarily correspond to a practical scenario. The formulation of an appropriate utility function in different practical conditions is still open ended and is discussed more in a later section.

Thus the optimization problem for single user is as follows

$$\max_{\alpha} u_p u_c$$
$$\sum_{i=1}^{3} \alpha_i = 1$$
$$\alpha_i M_0 \leq b_i \; \forall \; i \in \{1, 2, 3\}$$

Following graph shows allocation to different networks versus the bandwidth requirement of user, keeping the available bandwidths of the RATs as fixed (b = [500 500 500] Kb/s).

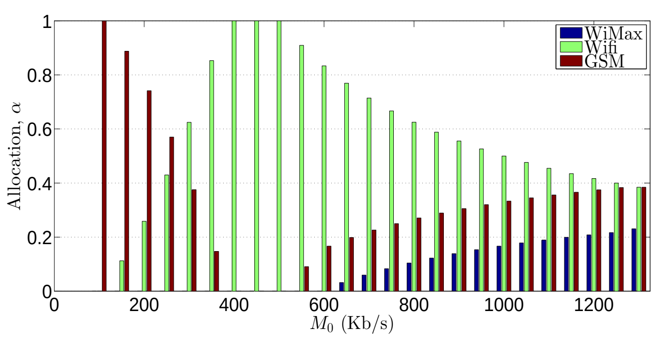

Fig. 3. Allocation values vs M_1.

In the figure, we can see that at lower bandwidth requirement of the user, GSM is preferred as the power consumption for GSM is significantly low. As the bandwidth requirement increases, the power benefits for using GSM decreases and the cost benefits for using Wifi increases. As such, user's requirement is split between GSM and Wifi. At 400 Kb/s, Wifi is both cost-efficient and power efficient than other RATs. Thus user uses only Wifi and not allocate anything to others. Above 500 Kb/s, as Wifi alone can't fulfil user's demand, user uses full available bandwidth of Wifi and allocates the rest to GSM. Above 600 Kb/s, though WiMax is less power-efficient than GSM, it has less cost/bandwidth and as such some allocation goes to WiMax. This demonstrates the compromise between the utilities of cost and power.

2) Multi-user case: For multi-user scenario, we consider a simple case of 2 users. We consider one of the user as in the previous case. This user is more sensitive to cost than power. This means that the utility changes sharply with change in cost; however the change in utility for the corresponding change in power is less. User 2 is modeled as more power sensitive, the context of sensitivity is as explained before. To capture the complex interaction between the users, we assume that user 1 and user 2 have bandwidth requirements of 400 Kb/s and 450 Kb/s respectively. The parameters characterizing the utility functions of user 2 is as follows -

Parameters	Cost utility	Power utility
x_α	0	0
x_β	5	18
x_m	3	8
ζ	2	2

TABLE II. PARAMETERS CHARACTERIZING UTILITY FUNCTION FOR USER 2

The optimization problem becomes -

$$\max_{\alpha} [U_1, U_2]$$
$$\text{subject to} \sum_{i=1}^{3} \alpha_{1i} = 1 \,, \sum_{i=1}^{3} \alpha_{2i} = 1$$
$$\alpha_{1i} M_1 + \alpha_{2i} M_2 \leq b_i \; \forall \; i \in \{1, 2, 3\}$$

where $U_1 = u_{1p}.u_{1c}$ and $U_2 = u_{2p}.u_{2c}$

For the following plots, x represents the available bandwidth of all the networks. For example, at x = 400 Kb/s, the available bandwidths are [400 400 400] Kb/s.

In the following results, we vary the available bandwidths with the networks keeping the requirements of both users as constant and observe the allocations of different users.

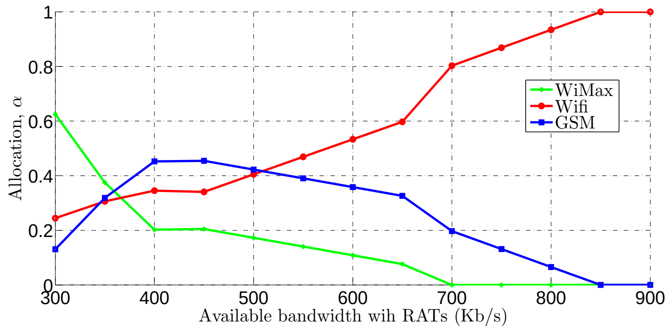

Fig. 4. Allocation for User 1 vs Available bandwidths of networks.

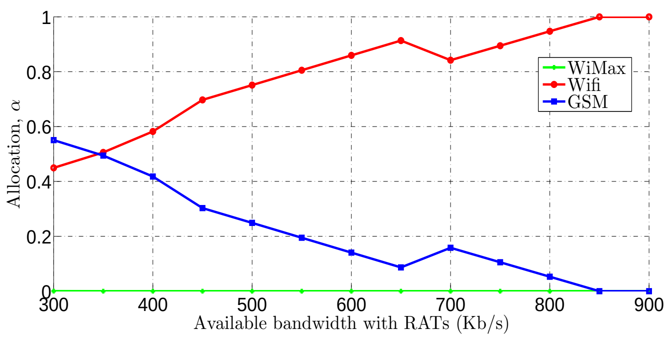

Fig. 5. Allocation for User 2 vs Available bandwidths of networks.

In the above figures, we can clearly see the compromise between the users. Initially, when b = [300 300 300], user 1, who is more cost sensitive , should have allocated most to Wifi. However, due to conflict of utility with user 2, it has to compromise by allocating more to WiMax(which is the next best in terms of cost). We also see that user 2, who is more power sensitive, don't allocate anything to WiMax in the entire range of bandwidth requirement from 300-1000 Kb/s. This is because WiMax is least power-efficient in this bandwidth range, and also due to the fact that GSM is not so preferable to user 1 as compared to user 2(due to higher cost/bandwidth). Also, the total bandwidth requirement of both the users is 850 Kb/s. So when the available bandwidth with the individual RATs exceeds 850 Kb/s(i.e. all the networks individually can support both the users), both the users use only Wifi, which is both power efficient and cost efficient in that bandwidth range.

Following figure shows the total allocation to different RATs vs their available bandwidths -

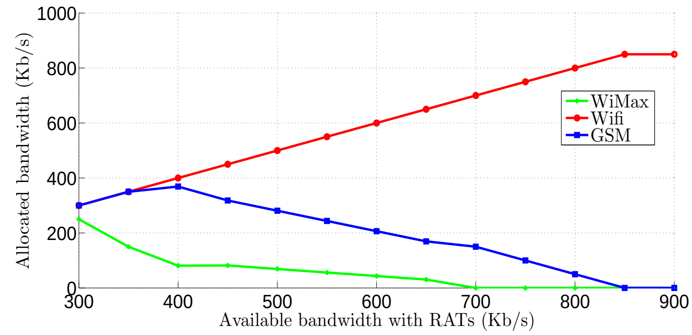

Fig. 6. Bandwidth allocated to different RATs vs Available bandwidths of RATs.

Initially, full bandwidth of GSM and Wifi is used, but not of GSM as it the utility it brings is less in that bandwidth range. We can see that the full available bandwidth of Wifi is used at all points. This is intuitively expected as Wifi is power and cost efficient. We also observe that WiMax and GSM are allocated lesser bandwidth as the available bandwidths of the RATs increase because users are allocating more and more to Wifi, and the benefits of using GSM and WiMax are decreasing.

IV. Conclusion and Future Work

The paper presents an approach to efficiently utilize the benefits of sharing the bandwidth requirement of users in heterogeneous networks scenarios. However, this formulation is valid for the scenario when the network parameters determining the allocation are static i.e. there is complete information about them before making the decision. However, parameters like Bit error rate(BER) are probabilistic in nature. To incorporate probabilistic parameters, a stochastic multi-criteria decision problem need to be studied.

Also, though the utility function forms are known, very little is done about the characterization of the utility function forms. There is no straightforward approach to determine the parameters for utility functions in a practical scenario.

It is envisioned that when the above improvements be incorporated, the decision problem will approach the real-world scenario and will give a better practical result.

Acknowledgment

The authors would like to thank...

References

[1] L. Wang, G.S. Kuo, "Mathematical Modeling for Network Selection in Heterogeneous Wireless Networks A Tutorial", *IEEE Communications Surveys & Tutorials* $Volume : 15, Issue : 1$

[2] H.D. Mustafa, S. Vijayan, S. Katta, S. Sharma, S.N. Merchant, U.B. Desai, "Green symbiotic heterogeneous networks" *IEEE 11th Consumer Communications and Networking Conference (CCNC), 2014*

[3] A. Tolli, P. Hakalin, H. Holma, "Performance Evaluation of Common Radio Resource Management (CRRM), *IEEE International Conference on Communications, 2002 - ICC 2002. (Volume:5)*

[4] P. Kosmides, A. Rouskas, M. Anagnostou, "Network Selection in Heterogeneous Wireless Environments, *18th International Conference on Telecommunications ICT, 2011*

[5] Quoc-Thinh Nguyen-Vuong, Yacine Ghamri-Doudane, Nazim Agoulmine, ”On Utility Models for Access Network Selection in Wireless Heterogeneous Networks”, *Network Operations and Management Symposium, 2008*

[6] Chen Y., Liu C., ”Multiobjective VAR planning using the goal-attainment method” , *IEE Proceedings-Generation, Transmission and Distribution 1994. 141, 227232.*

[7] K. Gomeza, D. Borub, R. Riggioa, T. Rasheeda, D. Miorandia, F. Granellib, ”Measurementbased Modelling of Power Consumption at Wireless Access Network Gateways”, *Computer Networks, Volume 56, Issue 10, 5 July 2012, Pages 25062521*

[8] Rahul Balani, ”Energy Consumption Analysis for Bluetooth, WiFi and Cellular Networks”

[9] Q. Song, A. Jamalipour, ”Network Selection in an integrated Wireless LAN and UMTS environment using Mathematical Modelling and Computing Techniques”, *Wireless Communications, IEEE (Volume:12 , Issue: 3),June 2005*