Heterogeneous Access Network(s) Selection in Multi-Interface Radio Devices

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***Abstract*—The advent of multi-interface smart radio devices brings the flexibility of simultaneous access to multiple heterogeneous access networks for making a significant improvement in network utilization by balancing network load and avoiding congestion. However, each heterogeneous access technology poses its own constraints in terms of data rate, coverage, availability, latency, packet loss rate, usage price etc. Thus, a novel selection mechanism must be devised to exploit the "best" available access network(s) to best serve the wireless users. Assuming users can ask for required amount of bandwidth from the ANs, we model the heterogeneous access network selection mechanism from a game theoretic perspective by formulating a user preference based utility expression. Then we find the optimal bandwidth demands and the number of packets to send via each of the selected AN for a radio node that maximizes its payoff. Theoretical analysis of the utility expression proves the existence of optimal bandwidth demand in single and multiple network selection, and the open/closed form expression for optimal bandwidth is presented. The results from the simulations conducted corroborate the theoretical optimal bandwidth and number of packets assigned for the selected network(s) with the corresponding experimental values.**

***Index Terms*—Heterogeneous access network, Game Theory, Multi-interface radios, Access Network selection**

I. Introduction

Proliferation of wireless access technologies (WiFi, UMTS, 3G, HSPA, LTE, WiMAX etc.) and ever-growing demand of new applications/services is hinting to exploit all the available access networks simultaneously for providing high throughput. As the coexistence of different radio access technologies is more a reality rather a hypothesis, the smart radio devices having multiple radio interfaces, will face the challenge of exploiting multiple available wireless technologies simultaneously, adapting to the dynamic availability of the access networks. The parallel access to multitude of access networks will significantly improve the network utilization, overall network latency, and provide a robust and ubiquitous connectivity for the radio device. The data-intensive applications can perform parallel data communication using multiple access networks (ANs), which thereby improves the average throughput, reliability of data delivery, and robust connectivity of the radio systems at minimum network delay. To provision high data rate services, with ubiquitous and pervasive connectivity with multiple wireless access networks, effective quantification models are required for classifying and measuring the offered service opportunities of the ANs. Using these models, an affordable set of ANs can be selected dynamically based on users' preferences and requirements by resolving the trade-off between user preferences and profitability of service providers.

As the heterogeneous access networks offer services of distinct data rate, interference temperature, reliability, usage price etc., a user might not get all favorable conditions in the period of its service. For instance, one technology might provide better throughput, but consumes more energy, whereas another offers reliable data delivery and charges high price. Also, the users might experience high congestion as the number of devices that select the same AN increases, or bandwidth demands for the AN increases. To analyze this conflict, we model the access network selection mechanism as a non-cooperative game. We formulate a user preference based payoff function, governed by the parameters like expected link capacity, cost of usage, latency, etc. Then We find the optimal amount of bandwidth to be asked for a user such that the overall utility is maximized.

As far as access network selection mechanisms are concerned, there are many works that focus on single access network selection, where mobile users face challenges to choose one among multiple access networks (see survey [1] and the references therein). Dynamic single network selection from the set of ANs such as WLAN and cellular system has been studied in [2] to improve the quality of service with minimum hand-offs user preferences evaluation techniques such as AHP and GRA. A utility and game theory (UGT) based network selection scheme is proposed in [3] by considering various traffic classes and mobility. The suitable network is selected from the candidate network's utility and preference value using a network preference cooperative game, which is solved to find the Nash equilibrium. To receive best services from candidate ANs like WCDMA, WLAN and WiMAX, [4] presented a game theoretical framework, where the weighted-sum payoff function considers service type, user preference, traffic state and signal strength, mobility, and battery drainage in each mode. The network with highest payoff then serves a particular service request of the user. In [5], the authors proposed an interface selection scheme considering battery power consumption, and user mobility with other existing parameters of the overlaying networks to improve users' QoS at minimum hand-overs. Authors of [6] model the game of selection of networks as a Bayesian network selection game, where the players are the users in a particular area with actions as the probability with which they will be selecting a network. The game is solved to find Bayesian Nash equilibrium by analyzing best response dynamics. An automatic network selection (ANS) mechanism is designed in [7] by considering the end-user's preference, link quality, and cost in their utility function. Authors of [8] studied the dynamics of end users and network operators by devising non-cooperative games with different cost functions and evaluated in terms of price of anarchy and price of stability.

The past literatures on heterogeneous AN selection have presented approaches of single-criteria optimization, and game theoretic solutions to select the single best suitable AN. The utility framework presented in previous works are formed by considering either bit error rate or interference constraints of the ANs, however the major parameters like network latency, monetary cost of usage, link capacity etc., has not been used together to formulate a realistic preference function for the users. Moreover, the scope of simultaneous access to multiple networks by the multi-interface radio nodes for maximizing the overall data delivery rate is still open to research. Also no work has undertaken the ability of radio devices to demand flexible amount of bandwidth based on their application requirements. Therefore, the first step to achieve the above untouched goals is to design a robust utility/preference function which might involve the basic decision parameters based on network related, device related, or service related factors, such as: bandwidth, link capacity, latency, monetary cost, battery status, number of interfaces, service category, etc. As the futuristic multi-interface devices can access multiple access networks at the same time, the challenge of selecting more than one access networks need to be addressed. In this paper, we study this dynamic multiple access network selection problem from a game theoretic perspective to find the optimal bandwidth demands from each selected AN such that their overall payoffs are maximized. A normalized utility expression is formulated to quantize the selected networks in terms of network latency, monetary cost, and link capacity. The model is analyzed to find out the optimal decision parameters either in closed or open form and the simulations are conducted to verify the theoretical analysis.

The rest of the paper is organized as follows: the system model is presented in section II. The network selection game along with the individual components of utility expression have been described in section III. Section IV presents the theoretical analysis to find the optimal bandwidth demand for both single network selection as well as multiple networks selection. The simulation results are reported in section V with explanation. Concluding remarks with future research directions are briefed in last section.

II. System Description And Assumptions

We consider a heterogeneous access network scenario with dynamic spectrum access where M access networks are available and offer distinct service opportunities with flexible price. To take advantage of such opportunities N multi-interface cognitive radio devices compete among each other for accessing either one or subset of M access networks (AN). Each radio device i $(1 \leq i \leq N)$ is equipped with multiple radio interfaces and possesses the capability of accessing to multiple ANs simultaneously provided that each interface can operate on exclusively one wireless AN. Figure 1 depicts a scenario, where multiple access networks such as WiFi, and cellular networks etc. coexist in a given region, and the radio nodes have options to choose one or multiple access networks among the set of accessible ANs. Hence the data communication between radio nodes can be parallelized using multiple links of different access networks, and thereby the individual as well as system level throughput can be improved. The reachable ANs provide different service opportunities at different costs, for example, WLAN provides cheapest shared wireless medium which is prone to interference, whereas LTE and WiMAX provide dedicated connectivity with high service cost. From Fig. 1, it can be seen that several radio nodes fall under the range of multiple ANs, hence the radio nodes face a decision situation of choosing the appropriate ANs based on nodes' application requirements and offered ANs' quality-of-service (QoS) offers. Given the flexibility of accessing multiple ANs simultaneously, it is assumed that radio systems can demand flexible amount of bandwidth from the network operators to run their spectrum sensitive applications efficiently. To resolve the trade-off between network resource utilization and user satisfaction, a game theoretic utility model is devised where the candidate access networks are evaluated based on the amount of bandwidth demanded from each AN and selected based on their aggregated payoff.

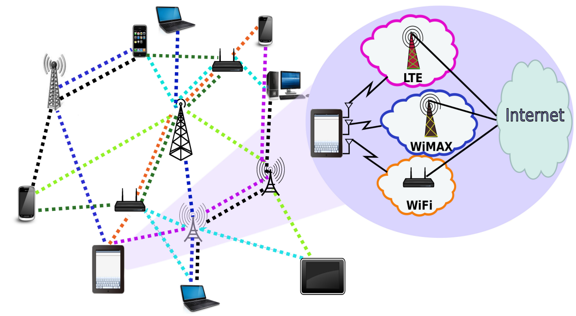


Fig. 1: A typical Heterogeneous Access Network Scenario

The heterogeneous ANs have different serving ability in terms of bit rate, degree of interference, and transmit power constraints etc. As the radio devices have the flexibility of demanding more bandwidth from the ANs, we assumed a cost model for each AN as a function of bandwidth demand from the considered AN. Additionally, the greedy nature of radio devices to achieve high data rate by demanding high bandwidth may not be satisfied due to the price constraints and high chances of getting collided with other competing nodes. So the overall interference ($\sum_{j \neq i} I_j$) from other devices who share the same network will reduce the expected data rate after a certain optimal bandwidth demand. The expected data rate to user i for accessing network m can be computed using Shannon's capacity theorem which is presented in Eqn.(1), where P_m is the received signal strength, N_{awgn} is the additive white Gaussian noise (AWGN), and B_m^i is the allocated bandwidth to user i. Thus it depends on how many other devices choose the same AN and the amount of bandwidth asked. With the estimated value of link capacity under a particular SINR value, the factors like end-to-end time delay, and monetary cost of usage per unit data byte and unit time can be computed for finding the overall preference value of the candidate access networks.

$$\mathbb{E}[C_m^i] = B_m^i \log\left(1 + \frac{P_m}{N_{awgn} + \sum_{j \neq i}, I_j}\right) \tag{1}$$

III. Network Selection Game Formulation

The problem of single or multiple network selection of ANs is modeled as a non-cooperative game ($G(N, S, U)$) in which N multi-interface cognitive radio devices act as players, and the strategy profile $S = \{S_1, S_2, ..., S_M\}$ represents strategy set of each player, where S_i constitutes the set of networks that player i wish to associate with, and $1 \leq |S_i| \leq M$. As it is clear that devices choosing a particular AN and demanding more bandwidth greedily might eventually lead to low throughput due to high congestion at higher expenses. Thus the players must choose the ANs wisely such that expected utility after demanding an optimal amount of bandwidth is maximized. For instance, high bandwidth demand from WLAN will increase the probability of collision, which might affect the response time due to increase in back-off number. However, a user might not face direct collisions in cellular networks as the bandwidth demand increases, rather the cost of extra bandwidth is high compared to WLAN. Therefore, the trade-off between user's willingness to pay and satisfaction on access link performance has to be resolved in the network selection game where, the payoff function for player i can be formulated based on following network related QoS factors: estimated end-to-end latency, expected capacity, and monetary cost involved for transferring a file to the base station of AN. In the following subsections, we formulate the payoff function using a cost-benefit approach and describe the optimization problem for selecting one or a subset of ANs.

A. Utility reward

To model the reward function, we assumed that user i requires to transfer a file of size F in a cost-effective way via the selected subset of access networks. Let's denote the allowed packet length of AN m as L_m bytes and the user i decides to send T_m^i number of packets via network m, where $T_m^i > 0$. For player any radio node $i \in N$, the total file transfer time using network m is indirectly proportional to the expected link capacity $\mathbb{E}[C_m^i]$. Therefore, the end-to-end delivery time of a packet will be high, if the capacity of the link is low. For successfully delivering a single packet to a destination radio node using AN m, the estimated duration will be $\frac{L_m}{\mathbb{E}[C_m^i]}$. We devise a Sigmoidal quality of service (QoS) function in terms of end-to-end delivery time, which explicitly emphasizes on how good the link capacity is on an average. If the average delivery time (t_{avg}^i) of player i to transfer T_m^i packets is close to maximum time (t_{max}^i), then the QoS function returns low reward value, whereas the reward gain is high when the average delivery time is minimal. The reward gain to user i after selecting subset of ANs S_i, can be expressed as

$$\mathbb{G}_i(S_i, S_{-i}) = \frac{1}{1 + e^{\left(b_i t_{avg}^i(S_i, S_{-i}) - \frac{t_{max}^i}{2}\right)}} \tag{2}$$

where, $b_i > 0$ is the weight coefficient that defines the steepness of reward function. $t_{avg}^i(S_i, S_{-i}) = \frac{1}{|S_i|} \sum_{m \in S_i} \frac{T_m^i L_m}{\mathbb{E}[C_m^i(m, S_{-i})]}$ is the average time spent for sending the whole file of size F via the set of ANs selected (S_i), and t_{max}^i is the time taken to send the whole file of size F bytes of data via the weakest link only.

B. Monetary Cost/Price Function

In the current data services scenario, the providers offer a minimum bandwidth for a constant price. However, in the futuristic pricing model, when the radio nodes demand more bandwidth as per their requirements, we assume that the price per unit bandwidth and unit time will increase depending on ANs' QoS offers. For example, the WiFi service offers cheapest data service at low usage cost and the increase in bandwidth demand may not increase the cost, rather the SINR value of the wireless medium might decrease exponentially, due to the shared nature of WLAN. On the other hand, the cellular or hybrid access networks such as LTE, WiMAX technologies are more reliable in terms of congestion and interference, but the cost of usage per unit bandwidth demand is very high, compared to WLAN. To design such cost functions for above mentioned access networks, we assume that each AN m asks a constant price of K_m units per bytes of data per unit time, until the player i's bandwidth usage is under a minimum value (B_m^{min}). As the radios can demand a flexible amount of bandwidth, the rational ANs will definitely charge high as the demand increases. Due to shared access medium of WLAN technology, demanding more bandwidth may not drastically increase the throughput, therefore, the cost function can be modeled as a slow starting function like linear, or piece-wise linear. However, high bandwidth in LTE and WiMAX networks can make large improvement in throughput due to low contention probability, hence the cost function can be modeled as any sharp increasing function, not only limited to exponential or quadratic. Assuming a linear cost function for WLAN and exponential cost function for the cellular/hybrid access networks, when the player i demands bandwidth B_m^i such that $B_m^{min} < B_m^i \leq B_m^{max}$, the cost function can be expressed in Eqn.(3), otherwise $K_m^i = K_m, \forall m \in M$.

$$K_m^i = \begin{cases} K_m + c_m a_m^{\alpha_m B_m^i} & \text{if } m \in \{\text{LTE, WiMAX}\} \\ K_m + c_m B_m^i & \text{if } m \in \text{WLAN} \end{cases} \tag{3}$$

where, $c_m, \alpha_m > 1$ are the cost coefficients of AN m, and a_m is the cost exponent decided by the provider of AN m.

Thus, assuming a user will be charged based on the number of bytes it pushes onto the selected links, and period of link usage, the estimated cost of usage charged to user i for transacting total $T_m^i L_m$ bytes of data with AN m can be

$$\mathbb{C}_i(S_i, S_{-i}) = \sum_{m \in S_i} \frac{(T_m^i L_m)^2}{\mathbb{E}[C_m^i(m, S_{-i})]} K_m^i \tag{4}$$

C. Overall Payoff Expression

The defined QoS factors represent different dimensions of measuring quality of service from the users' perspective, however QoS parameters are not only limited to these factors. In formulating the overall payoff expression, the radio terminals always aim to find a subset of ANs that can provide better link capacity at a minimum cost, so that the end-to-end delivery delay is minimal. In this work, we assume that the transmit power in individual access networks is constant and maximum as per standard. As each player $i \in N$ has the privilege of demanding more bandwidth and can decide percentage of packets it wants to send through a particular network, the aggregate utility function of player i (U_i) is function of demanded bandwidths $\{B_m^i : m \in S_i\}$ and number of packets (T_m^i) it wants to push through network m. The aggregate utility expression after reducing the usage cost for the complete transaction can be expressed as

$$U_i(S_i, S_{-i}) = \frac{a_i}{1 + e^{\left(b_i t_{avg}^i - \frac{t_{max}^i}{2}\right)}} - \sum_{m \in S_i} \frac{(T_m^i L_m)^2 K_m^i}{\mathbb{E}[C_m^i(m, S_{-i})] F t_{max}^i}$$

where, a_i is the scaling constant, $\sum_{m \in S_i} T_m^i L_{m_i} = F$, and t_{max}^i is the maximum time consumed to transfer the complete file. The optimization problem is to find the optimal bandwidth demand vector $\{(B_m^i)^* : m \in S_i\}$, which maximizes the aggregated utility $U_i(S_i, S_{-i})$ of player i.

IV. Theoretical Analysis

Without loss of generality, here we analyze the aggregate payoff expression from player i's perspective to find the optimal amount of bandwidth from the set of selected access networks, such that the aggregate utility is maximized. First, we analyze to find the optimal bandwidth demand theoretically by selecting only single AN from the set of N networks. Then we generalize for multiple ANs selection to find the optimal bandwidth demands from each AN $m \in S_i$ individually keeping number of packets sent T_m^i constant and vice versa. Finally, the existence of an optimal bandwidth demand $(B_m^i)^*$ is proved.

A. Single Network Selection

Considering the single network selection scenario, where the radio node can select one network from the set of available networks, we now analyze to obtain optimal bandwidth demand $(B_m^i)^*$ for WLAN and LTE/WiMAX scenario. To find $(B_m^i)^*$, we equated the first order partial, $\frac{\partial U_i}{\partial B_m^i}$ to zero and solved to find $(B_m^i)^*$. As per our assumption on WLAN environment, the cost is a linear function presented in Eqn.(3), whereas the SINR degradation varies exponentially. The expression for $(B_m^i)^*$ in WLAN is not in a closed form, rather the open form solution is given in Eqn.(5).

$$\left[\left(\frac{\mathbb{E}[C_m^i]}{B_m^i} - \frac{B_m^i 10^{SINR_m} SINR_m \log(10)}{10(1 + SINR_m)\kappa}\right) \times \left(\frac{(R_m^i - 1)}{(R_m^i)^2} + \frac{K_m^i}{t_{max}^i}\right)\right] - \frac{\mathbb{E}[C_m^i] c_m}{B_m^{diff} t_{max}^i} = 0 \tag{5}$$

where, $SINR_m(dB)$ varies exponentially according to $e^{(B_m^{max} - B_m)/\kappa}$, $B_m^{diff} = B_m^{max} - B_m^{min}$ and $R_m^i = 1 + e^{\left(b_i T_m^i - \frac{t_{max}^i}{2}\right)}$.

Numerical analysis can be made to find the critical B_m^* by varying the bandwidth demand so that Eqn.(5) is satisfied. We also find the generic open form solution for the optimal bandwidth demand in case of LTE/WiMAX access technology by equating the first order differential to zero, which is presented as Eqn.(6).

$$\left[\left(\frac{\mathbb{E}[C_m^i]}{B_m^i} - \frac{B_m^i \kappa_1}{(1 + SINR_m)}\right) \times \left(\frac{(R_m^i - 1)}{(R_m^i)^2} + \frac{K_m^i}{t_{max}^i}\right)\right] - \left[\frac{\mathbb{E}[C_m^i] \log(a_m) a_m^{B_m^i \alpha_m}}{\alpha_m a_m^{diff} t_{max}^i}\right] = 0 \tag{6}$$

where, $SINR_m(m \in \{\text{WiMAX, LTE}\})$ varies linearly according to the following equation, $SINR_m(dB) = \kappa_1(B_m^{max} - B_m) + \kappa_2$ and $a_m^{diff} = a_m^{\alpha_m B_m^{max}} - a_m^{\alpha_m B_m^{min}}$. After finding the critical bandwidth demands using numerical analysis, we conducted the second derivative test and found that $\left(\frac{\partial^2 U_i}{\partial {B_m^i}^2}\right)_{B_m^i = (B_m^i)^*} < 0$, for both the considered scenarios, which proves the critical points are maxima.

B. Two Network Selection

For the sake of showing the existence of optimal bandwidth demand while selecting multiple access networks, we considered two networks for simultaneous access. Using the similar approach, we equated the first order differential of U_i w.r.t B_1, B_2 by considering WLAN and LTE/WiMAX to zero for finding the optimal bandwidth demands and the open form conditions are presented in Eqn.(7) and Eqn.(8).

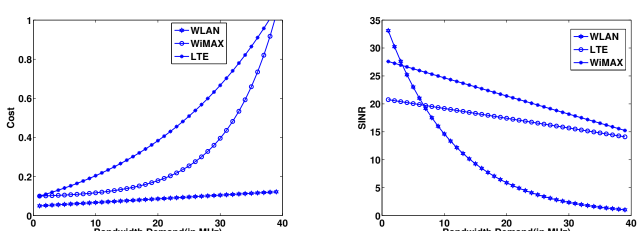
$$\left[\left(\frac{\mathbb{E}[C_1^i]}{B_1^i} - \frac{B_1^i 10^{SINR_1} SINR_1 \log(10)}{10(1 + SINR_1)\kappa}\right) \times \left(\frac{b_i(R_{avg}^i - 1)}{2(R_{avg}^i)^2} + \frac{T_1^i L_1 K_1^i}{t_{max}^i}\right)\right] - \frac{T_1^i L_1 \mathbb{E}[C_1^i] c_1}{B_{diff} t_{max}^i} = 0 \tag{7}$$

$$\left[\left(\frac{\mathbb{E}[C_2^i]}{B_2^i} - \frac{B_2^i \kappa_1}{(1 + SINR_2)}\right) \times \left(\frac{b_i(R_{avg}^i - 1)}{2(R_{avg}^i)^2} + \frac{T_2^i L_2 K_2^i}{t_{max}^i}\right)\right] - \left[\frac{T_2^i L_2 \mathbb{E}[C_2^i] \log(a_2) a_2^{B_2^i \alpha_2}}{\alpha_2 a_2^{diff} t_{max}^i}\right] = 0 \tag{8}$$

where, $R_{avg} = 1 + e^{\left(b_i t_{avg}^i - \frac{t_{max}^i}{2}\right)}$ and using similar numerical analysis approach we can find the optimal bandwidth demand by keeping the number of packets fixed for the both networks. The simulated results have been reported in the next section, where we could explicitly find the optimal bandwidth demands for the selected networks. Using similar approach, we can generalize the theory for selecting more than two networks to find the optimal bandwidth demands for the selected ANs.

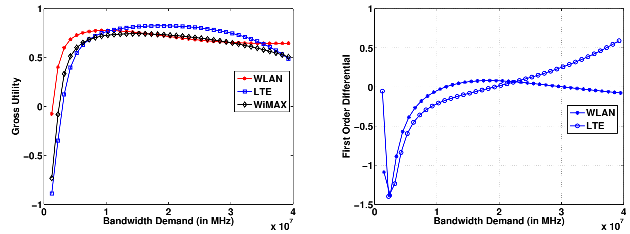
V. Results and Discussion

To simulate the heterogeneous access network selection, we considered the following three wireless access technologies: WLAN, LTE, and WiMAX. In the non-cooperative game, we assumed that the multi-interface CR nodes can decide to select either one or two best networks from the available ANs. The players evaluate the aggregate utility based on the number of ANs they select. The simulations were conducted in Matlab version 8.1 with following set of parameters for individual access networks. The flexibility of bandwidth demand is provided by each access networks in the range of 1.5 MHz to 40 MHz and the packet length is assumed as the size of a TCP packet. To validate our theoretical analysis, we simulated each of the scenarios individually by considering the radio nodes seek to send a file of size, $F = 60$MB via the selected ANs and the unit pricing functions for the individual access network is shown in Figure 2(a). Intuitively, the cost of demanding more bandwidth from LTE and WiMAX access technologies is higher compared to WLAN technology due to their reliable and congestion-free services. The former ANs provide dedicated communication medium to protect its incumbents from interferences, whereas WLAN cannot provide a guaranteed QoS due to its shared medium access. Hence, high bandwidth demand in WLAN may not provide high throughput rather increases the possibility of network congestions. The LTE access network is an advanced technology which provides guaranteed high data rate with bounded interference temperature. Therefore, LTE costs more compared to WiMAX, whereas WLAN offers cheapest communication medium compared two others ANs. Considering the above intuitions, we assume a linear cost function for WLAN and exponential cost functions for LTE, and WLAN, which increase with rising bandwidth demands from multi-interface CR nodes. Due to the possibility of cross-channel interference upon rising bandwidth demand, we assume a linear SINR degradation function for WiMAX, and LTE ANs, however shared medium access degrades SINR exponentially in WLAN, which is presented in Fig. 2(b). Considering these defined parameters, the conducted simulation results are reported here for selecting single as well as two ANs.



(a) (b)

Fig. 2: (a) Cost/Pricing function (b) SINR degradation function per unit bandwidth demand



(a) (b)

Fig. 3: (a) Optimal Bandwidth Demands in Single AN Selection, (b) Numerical analysis result for theoretical optimal bandwidth demand

A. Single Network Selection Scenario

When a player selects only one AN, all packets of the corresponding file will be pushed through that particular network. From the Fig. 3(a), it can be observed that sending the whole file via WLAN is as good as other two networks because of its high link capacity at minimum bandwidth demand, where probability of congestion is small. However LTE and WiMAX charges more price compared to WLAN but provides exclusive access to the spectrum bands and estimated capacity is high at high bandwidth region, due to which the gross utility is maximized at high bandwidth demand. As bandwidth demand increases, the shared medium of WLAN becomes congested and the packet delivery time increases compared to respective cost of extra bandwidth. Therefore, the overall gross utility decreases gradually with increasing bandwidth demand. The optimal bandwidth demand for WLAN and LTE found through the discrete band simulation are 10.25 MHz and 19.25 MHz respectively. And to validate the theoretical analysis with the result found, we performed numerical analysis using equation 5, 6, for WLAN and LTE respectively to find the theoretical optimal bandwidths. The result of numerical analysis for single network selection, presented in Fig. 3(b) and plots of the first order differential equations of WLAN and LTE hits zero at 10.5 MHz and 20.25 MHz respectively, which are close to the results obtained from simulation. Therefore, demanding high bandwidth from WLAN will not beneficial compared to LTE/WiMAX.

B. Multiple Network Selection Scenario

We also simulated for the two network selection scenario of choosing WLAN (net # 1) and WiMAX (net # 2), where we varied the percentage of packets sent via WiMAX and its corresponding bandwidth demand to find the optimal bandwidth required for each candidate AN. For this experiment the bandwidth of WLAN technology is kept fixed as 20 MHz. From Fig. 4(a), it can observed that there exists a maxima for different percentage ratio of packet sending via each network, but the gross utility at maxima depends on how the access links are utilized on an average. Under-utilizing the high efficient link will reduce the utility, however utilizing both the access links equally gives better utility compared to biased usage of any single AN.

We simulated another instance of two network selection

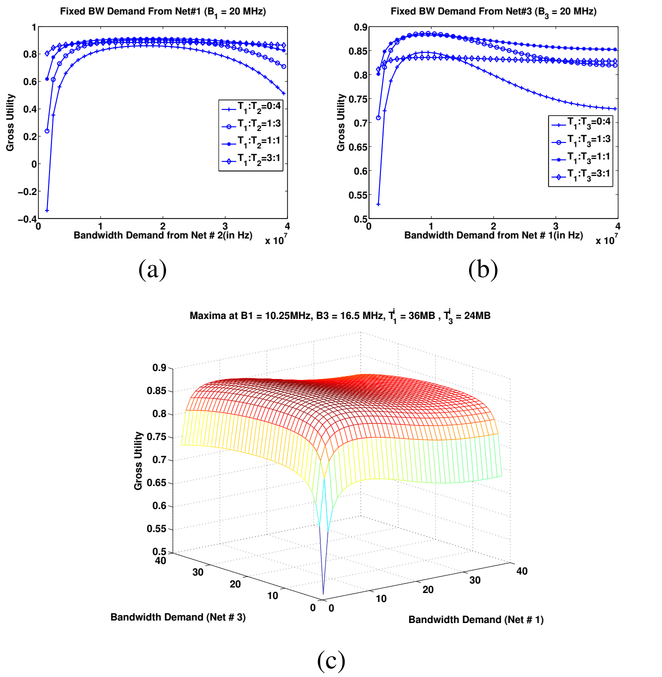


Fig. 4: (a) Two AN Selection with varying BW demand from WiMAX and $T_1 : T_2$ ratio, (b) Two AN Selection with varying BW demand from LTE and $T_1 : T_3$ ratio, (c) Two AN Selection with varying BW demand from WLAN and LTE

scenario of choosing WLAN (net # 1) and LTE (net # 3) where we varied the percentage of packets sent via WLAN and bandwidth demand to find the optimal WLAN bandwidth demand for ANs selected. For this experiment the bandwidth of LTE technology is kept fixed as 20 MHz. From Fig. 4(b), it can observed that the optimal bandwidth for WLAN is less compared to the previous scenario. This happens due to the severe link degradation as the demand of bandwidth increases. Therefore, LTE network can provide better service in this case compared to WLAN, so it is useful to utilize the LTE link maximally. The plot shows clearly that when the packet sending ratio is 1:3, maximum utility can be achieved due to high utilization of LTE link.

Finally, we considered two networks WLAN (net # 1) and LTE (net # 3), for the simultaneous communication, where all parameters such as bandwidth demands and number of packets sent via each network are need to be optimized. From the Fig. 4(c), we can observe that when bandwidth demand from both networks is high, the gross utility decreases due to high monetary cost and SINR degradation in WLAN. As per our simulation, it is found that gross utility is maximized, when the bandwidth demands from WLAN, and LTE is not more or less than 16.5MHz, 10.25 MHz respectively provided 60% of the whole file is sent via WLAN and rest is transferred via LTE. This division of whole file by 3:2 ratio is optimal because WLAN offers high estimated capacity at low bandwidth demand, whereas sending large packets via LTE costs more compared to WLAN, which eventually decreases the gross payoff of the radio nodes.

VI. Conclusions and Future Research Directions

This paper addresses the heterogeneous access network selection problem from a game theoretic perspective by devising a realistic utility formulation. As most of the prior works looked into the problem to find a single and "always best connected" access network, we modeled the problem from multiple access network selection point of view. The players are more interested in using multiple access networks simultaneously with the flexibility to demand more spectrum resources to maximize their overall performance using the selected ANs effectively. We designed an aggregate utility function for the smart radio devices by considering three major components that a user concerns about, such as network latency, estimated capacity under SINR variation, and the monetary cost per unit time and unit data bytes transacted. Theoretical analysis of the payoff function for both single as well as multiple networks is conducted and it is proved that there exists an explicit maxima for optimal bandwidth request to the selected AN beyond which the radio node cannot gain more. We simulated two scenarios of selecting single-best and two-best networks to validate our theoretical analysis, which corroborates with the simulation results. In future, we will extend this research to analyze network selection problem, where multiple parameters can be optimized simultaneously under the constraints of dynamic availability of access networks spatially as well as temporally and develop adaptive heuristics to maximize the network throughput by sending optimal amount of packets through each AN.

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