

# 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 (ANs) for making a significant improvement in the network utilization by balancing the 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 a 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 using three major parameters: expected data rate, latency, and usage cost. Then we analyze the utility model to find the users’ optimal bandwidth demands from the selected ANs that maximize their net payoff. Theoretical analysis of the utility expression proves the existence of optimal bandwidth demand in the single and multiple network selection, and we derive the open/closed form expression for optimal bandwidth too. 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 than a hypothesis, the smart radio devices with 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 [1] to multitude of access networks will significantly improve the network utilization, overall network latency, and provide robust and ubiquitous connectivity for the radio devices. The data-intensive applications [2] can perform parallel data communication using multiple flows [3] to various ANs, which thereby improves the average throughput, reliability of data delivery, and robust connectivity of the radio systems at minimum network delay. To provision such services through multiple wireless ANs, effective quantification models are required for classifying and measuring their offered service opportunities. Using these models, an affordable set of ANs can be selected dynamically

based on users’ requirements by resolving the trade-off between their preferences and profitability of service providers.

As the heterogeneous access networks offer services of distinct data rate, interference temperature, reliability, usage price, etc., the users might not get all favorable conditions in the period of their service. For instance, one technology might provide better throughput, but consume more energy, whereas another might offer reliable data delivery but charge a 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 by formulating a user preference based payoff function, governed by the following parameters: expected link capacity, cost of usage, and latency. Then, we find the optimal amount of bandwidth to be asked for a user such that its expected overall utility is maximized.

As far as access network selection mechanisms are concerned, many works focus on single access network selection, where mobile users face challenges to choose one among multiple access networks (see survey [4] and the references therein). Dynamic single AN selection among WLAN and cellular system has been studied in [5] using preferences evaluation techniques such as AHP and GRA. A utility and game theory based AN selection scheme is proposed in [6] by considering various traffic classes and mobility, where the network preference cooperative game is solved to find the Nash Equilibrium (NE) strategy. To receive best services from candidate ANs like WCDMA, WLAN and WiMAX, authors of [7] have presented a game having a weighted-sum payoff function that considers service type, user preference, traffic state and signal strength, mobility, and battery drainage. The network with highest payoff then serves a particular service request of the user. In [8], the authors have proposed an interface selection scheme considering battery power consumption, and user mobility parameters of the overlaying networks to improve users’ quality of service (QoS) at minimum handovers. Authors of [9] have modeled the game of AN selection as a Bayesian game, where the players are the users in a particular area with actions as the probability with which they will be selecting a network and solved for the Bayesian NE by analyzing the best response dynamics. An automatic network selection mechanism is designed in [10] by considering the end-user’s preference, link quality, and cost in their

utility function. Authors of [11] have 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 such as network latency, monetary cost of usage, link capacity, etc., have not been utilized. 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 a flexible amount of bandwidth based on their application requirements. Therefore, our first step to achieve the above untouched goals is to design a robust utility/preference function which involves the above mentioned decision parameters. As the futuristic multi-interface devices can access multiple ANs simultaneously with the help of multipath TCP protocol [3][12], the challenges of multi-criteria based selection of one or more ANs need to be addressed thoroughly. In this paper, we study the dynamic multiple AN selection problem from a game theoretic perspective using the robust utility function and find the optimal bandwidth demands from the selected ANs such that users' net benefit is maximized. The game is analyzed to derive the open/closed form expressions for the optimal bandwidth demands 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 are described in section III. Section IV presents the theoretical analysis to find the optimal bandwidth demand for both single network selection as well as two networks selection. The simulation results are reported in section V. Concluding remarks with future directions are briefed in the section VI.

## II. SYSTEM DESCRIPTION AND ASSUMPTIONS

We consider a heterogeneous access network scenario where  $M$  access networks are available and offer distinct services at a flexible price. To take advantage of such opportunities,  $N$  multi-interface radio devices compete among each other for accessing either one or a 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 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, WiMAX, and cellular network coexist in a given region, and the radio nodes have options to choose one or multiple ANs. Hence the data communication between radio nodes can be parallelized using multiple paths via different access networks, and thereby the individual as well as system level throughput can be improved. The reachable ANs provide

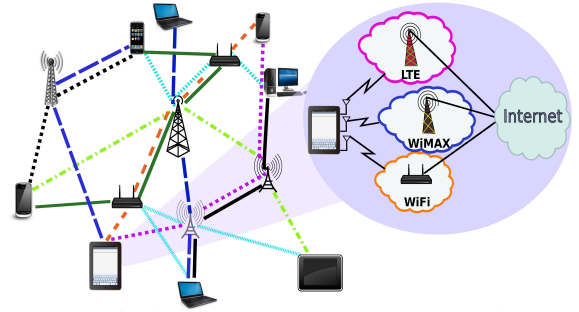


Fig. 1: A typical Heterogeneous Access Network Scenario

different service opportunities at different costs; for example, WLAN provides the cheapest shared wireless medium which is prone to interference, whereas LTE and WiMAX provide dedicated connectivity with high service cost. Thus, the radio nodes face a decision situation of choosing the appropriate ANs based on their application requirements and offered QoS of ANs. Given the flexibility of accessing multiple ANs simultaneously, it is assumed that radio systems can demand flexible amounts 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, we devise a game theoretic utility model, where the candidate access networks are evaluated and selected based on the users' rewards obtained for their bandwidth demands.

To limit the bandwidth over-utilization, we assumed a cost model for each AN as a function of bandwidth demand. 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 colliding with other competing nodes. Hence the expected data rate of an AN decreases as the total interference ( $\sum_{j \neq i} I_j$ ) increases due to many users sharing the same medium. Therefore, the wireless users look forward to choosing multiple ANs in such a way that they receive higher data rate and at the same time the cost of usage is minimized for their bandwidth demands. 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 the throughput of the user  $i$  depends on how many other devices choose the same AN  $m$  and the amount of bandwidth asked ( $B_m^i$ ). With the estimated value of link capacity under a particular signal-to-interference-noise ratio (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 ANs.

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

## III. NETWORK SELECTION GAME FORMULATION

The problem of single or multiple AN selection is modeled as a non-cooperative game  $G(N, S, U)$  in which  $N$  multi-interface radio devices act as players, and the strategy profile

$S = \{S_1, S_2, \dots, S_N\}$  represents the strategy set of each player, where  $S_i$  constitutes the set of ANs, out of  $M$  available ANs, that player  $i$  chooses to associate with, and  $1 \leq |S_i| \leq M$ . The game is played in a simultaneous and uncoordinated manner, where the players receive a reward at the end of game interaction depending on their own action and other players' choices too. If user  $i$ 's strategy is same as all other players  $j \neq i$ , then user  $i$  either incurs high cost or communicates in a highly congested wireless medium at low cost. Additionally, if all the users demand more bandwidth from the same AN, then they might have to share the medium so that the resource outage scenario can be avoided. Hence the utility reward to one player is guided by not only its own action but also actions of all other players too. Therefore, the trade-off between users' 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 using an AN. In a real-world deployment, the former two parameters can be estimated using Shannon's theorem, where SINR can be estimated using awgn SINR estimation techniques [13], and latency can be computed depending on the packet size and previously estimated link capacity. In the following subsections, we detail the payoff function formulation using the above mentioned parameters via a cost-benefit approach and describe the underlying optimization problem for the ANs selection.

#### A. Utility reward

To model the reward function, we assume that user  $i$  requires transfer of 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 QoS function in terms of end-to-end delivery time, which explicitly emphasizes 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

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

where,  $b_i > 0$  is the weight coefficient that defines the steepness of the 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' service qualities. For example, the WiFi service offers the cheapest data service at low usage cost; the increase in bandwidth demand may not drastically increase the cost, rather the SINR value of the wireless medium might decrease exponentially, due to the shared nature of WLAN medium. On the other hand, the cellular or hybrid access networks such as LTE and WiMAX technologies are more reliable in terms of congestion and interference, so the cost of usage per unit bandwidth demand is very high compared to WLAN.

To design such cost functions for the above mentioned ANs, 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. In WLAN technology, cost of access should not be high on demanding more bandwidth as it 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 significant improvements in throughput due to low contention probability, hence the providers may model the cost function as any sharp increasing function, but 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  $K_m^i = K_m, \forall m \in M$ .

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

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

Assuming user  $i$  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

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

#### C. Overall Payoff Expression

The defined components represent various dimensions of measuring QoS from the users' perspective, however these parameters are not only limited to only three. 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 minimum. 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 what percentage of packets it wants to send through a particular AN, the aggregate utility function of player  $i$  ( $U_i$ ) is a 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 subtracting the usage cost for the complete transaction can be expressed as

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

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  $\{(B_m^i)^* : m \in S_i\}$  for the selected ANs, 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 ANs, 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 prove the existence of an optimal bandwidth demand  $(B_m^i)^*$  is proved for two selected ANs, assuming the number of packets sent ( $T_m^i$ ) via AN  $m$  is constant.

##### 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).

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

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  $R_m^i = 1 + e^{(b_i T_m^i - \frac{t_{max}^i}{2})}$ .

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).

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

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  $\left( \frac{\partial^2 U_i}{\partial B_m^i} \right)_{B_m^i = (B_m^i)^*} < 0$ , 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 consider two networks for simultaneous access. Using the similar approach, we equate 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).

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

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

where,  $R_{avg} = 1 + e^{(b_i t_{avg}^i - \frac{t_{max}^i}{2})}$  and using similar numerical analysis approach we can find the optimal bandwidth demand by keeping the number of packets fixed for 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. Similar approach can be used to 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 consider the following three wireless access technologies: WLAN, LTE, and WiMAX. In the non-cooperative game, we assumed that the multi-interface radio 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

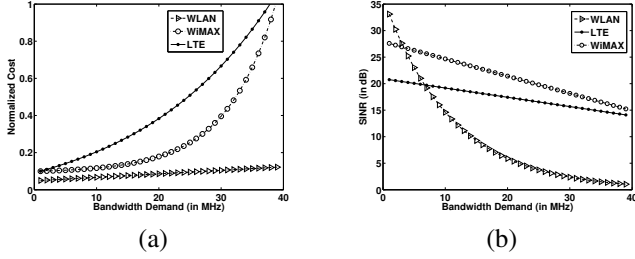


Fig. 2: (a) Cost/Pricing function (b) SINR degradation function per unit bandwidth demand

8.1 with the following set of parameters for individual access networks. The flexibility of bandwidth demand is provided by each access network in the range of 1.5 MHz to 40 MHz and the packet length is assumed as the size of a standard TCP packet. To validate our theoretical analysis, we simulated each of the scenarios individually, where the radio nodes seek to send a file of size,  $F = 60\text{MB}$  via the selected ANs, however the size of file that needs to be transferred is not capped to the mentioned value, rather a file of any size can be used here.

The unit pricing function for the considered access networks is shown in Figure 2(a) where, we assume that the cost of demanding more bandwidth from LTE and WiMAX access technologies is higher compared to WLAN due to their reliable and congestion-free services. The former ANs provide dedicated communication mediums to protect its incumbents from interferences, whereas WLAN may not provide a guaranteed QoS due to its shared medium access. Hence, high bandwidth demand in WLAN may not provide high throughput but rather increases the possibility of network congestions; whereas LTE is an advanced technology which provides guaranteed high data rate with bounded interference temperature. Considering the above intuitions, we assume a linear function to represent the normalized cost for WLAN access with coefficients  $c_m = 0.004$  and  $K_m = 0.07$ . For WiMAX and LTE, we assume normalized power functions with coefficients ( $c_{wimax} = 0.1, a_{wimax} = 1.58$ ) and ( $c_{lte} = 0.15, a_{lte} = 2.7$ ) respectively. However, any increasing functions other than linear/exponential is applicable to model our cost function, provided it satisfy the above described assumptions. 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 the shared medium access degrades SINR exponentially in WLAN, which is presented in Fig. 2(b). Considering these parameters, we report the simulation results in the following for selecting single as well as two ANs.

#### 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 the other two networks because of its high link capacity at minimum bandwidth demand, where probability of congestion is small. However LTE and WiMAX charge more price compared to WLAN but provides exclusive

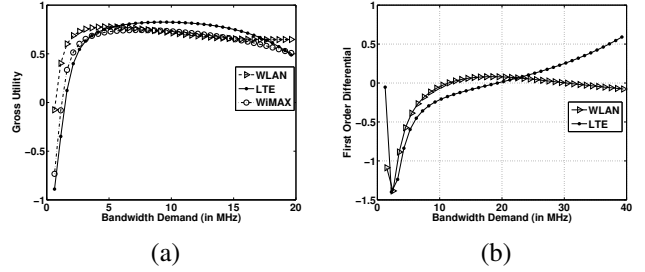


Fig. 3: (a) Optimal Bandwidth Demands in Single AN Selection, (b) Numerical analysis result for theoretical optimal bandwidth demand

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 equations 5 and 6, for WLAN and LTE respectively to find the theoretical optimal bandwidths. The result of numerical analysis for single network selection is presented in Fig. 3(b). The 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 be 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 be 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 the two network selection 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 be 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.

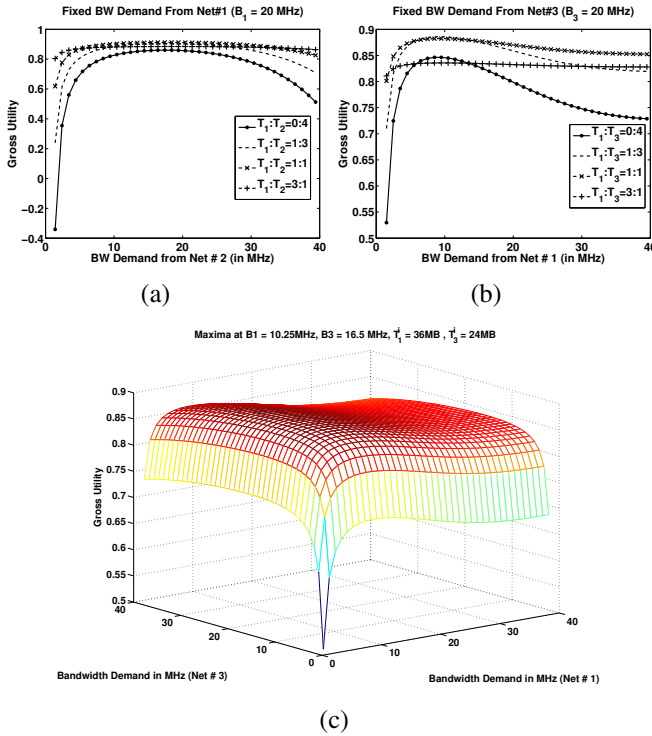


Fig. 4: (a) Two AN Selection with varying BW demand from WiMAX and  $T_1 : T_2$  ratio, (b) Two AN Selection with varying BW demand from LTE and  $T_1 : T_3$  ratio, (c) Two AN Selection with varying BW demand from WLAN and LTE

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 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 are not more or less than 16.5MHz and 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 a 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 is concerned about, such as network latency, estimated capacity under SINR variation, and the monetary cost per unit time and unit data bytes. 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 the future, we will extend this research to analyze the 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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