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A Unified Approach Assignment Framework For Heterogeneous Network Access

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Abstract-We consider a scenario where devices with multiple networking capabilities access networks with heterogeneous characteristics. In such a setting, we address the problem of efficient utilization of multiple access networks (wireless and/or wire line) by devices via optimal assignment of traffic flows with given utilities to different networks. We develop and analyze a device middleware functionality that monitors network characteristics and employs a Markov Decision Process (MDP) based control scheme that in conjunction with stochastic characterization of the available bit rate and delay of the networks generates an optimal policy for allocation of flows to different networks. The optimal policy maximizes, under available bit rate and delay constraints on the access networks, a discounted reward which is a function of the flow utilities. The flow assignment policy is periodically updated and is consulted by the flows to dynamically perform network selection during their lifetimes. We perform measurement tests to collect traces of available bit rate and delay characteristics on Ethernet and WLAN networks on a work day in a corporate work environment. We implement our flow assignment framework in ns-2 and simulate the system performance for a set of elastic video-like flows using the collected traces. We demonstrate that the MDP based flow assignment policy leads to significant enhancement in the QoS provisioning (lower packet delays and packet loss rates) for the flows, as compared to policies which do not perform dynamic flow assignment but statically allocate flows to different networks using heuristics like average available bit rate on the networks.

1. INTRODUCTION

Several networking technologies have evolved and become popular over the past few decades. Ethernet, DSL, cellular wireless networks, and IEEE 802.11 based wireless local area networks have become widely deployed and increasingly accessible. Existing networks tend to be heterogeneous in their attributes such as the supporting infrastructure, protocols, signaling mechanisms, offered data rates, etc. With the realization that several technologies will continue to coexist and there will be no clear winner, the drive towards convergence of networks is gaining momentum. Integration of heterogeneous access networks is part of the 4G network design [1]. IEEE 802.21 [2] is delineating a framework to enable handovers and interoperability between heterogeneous wireless and wire line networks. The IP Multimedia Subsystems (IMS) [3] has defined overlay architecture for providing multimedia services on top of heterogeneous networks.

It is today commonplace to have electronic devices with multiple networking capabilities. Personal computers and laptops typically come equipped with a built-in WLAN card, a PCMCIA slot, and an Ethernet port. PDAs with WLAN and GPRS connectivity are becoming popular. As a multitude of bandwidth demanding applications such as IPTV and Internet Video run on devices, a single network may often not be sufficient to meet the requirements of the applications. Several interesting scenarios may be envisioned. Imagine a user in a corporate setting participating in a video conference call via her device having both Ethernet and IEEE 802.11g connectivity.

While engaged in the conference proceedings, the user is uploading content on a remote server for the participants to access, and at the same time needs to retrieve some files from the server. Several traffic flows are hence created by the device which dynamically monitors the networks at its disposal. The device then routes the flows via these networks and dynamically reassigns them to different networks based on the varying network characteristics like available bite rate (ABR) and delay.

While the distribution of traffic flows amongst different networks can enable better network utilization than single network use at a time, the variation in network characteristics like ABR and delay makes the problem of flow assignment challenging. Especially when the access networks include wireless links, the network characteristics variations require robust modeling techniques and stochastic tools. In this work, we address the problem of optimal allocation of flows on a device onto multiple networks with heterogeneous characteristics.

We approximate the ABR and delays of the networks to represent the states of a Markovian system. We then develop and analyze a *middleware* functionality that monitors the network characteristics and uses a Markov Decision Process (MDP) [4] based control scheme to suggest a network to which a flow with given utility should be assigned. The MDP selects a network that maximizes a discounted reward which is represented as a function of flow utility and the impact of the flow assignment on the system. The flow utility in turn depends on the ABR and delay offered by a network to the flow. The MDP based flow assignment policy is updated periodically by the middleware and is dynamically consulted by the flows during their lifetimes to select the suggested networks. We implement the flow assignment framework in ns-2 [5] and collect ABR and delay traces for Ethernet and WLAN networks in a real-world setting. We then evaluate the performance of high bit rate elastic video-like flows using the simulated framework and demonstrate that MDP based flow assignment scheme results in significantly better QoS provisioning for the flows in terms of lower packet delays and packet loss rates.

In general, the problem of efficient utilization of multiple networks via suitable allocation of traffic flows has been explored in different settings and from different perspectives. A game theoretic framework for bandwidth allocation for elastic services in networks with fixed capacities has been addressed in [6–8]. Our work on the other hand is motivated by the practically observed and varying characteristics of networks that are widely deployed today. Packet scheduling for utilization of multiple networks has been investigated in [9].The opportunistic scheduling of packets has the drawback of needing a packet level scheduler and frequent packet reordering at the receiver. In our work, we thus focus on flow based scheduling for heterogeneous networks. A solution for addressing the handoff, network selection, and autonomic computation for integration of heterogeneous wireless networks has been presented in [1]. The work, however, does not address efficient simultaneous use of heterogeneous networks and does not consider wire line settings. Similarly, the work [10] focuses on selection techniques for users to get connected to the most suitable network in terms of user defined QoS criteria, and does not address a multi-homed device scenario. In [11], the authors have explored design of a network comprised of wide area and local area technologies where user devices select among the two technologies in a greedy fashion so as to maximize a utility function based on wireless link quality, network congestion, etc. The work does not address simultaneous use of the two technologies by the users. Recently, a cost price mechanism that enables a mobile device to split its traffic amongst several IEEE 802.11 access points based on throughput obtained and price charged, was proposed in [12]. However, the work does not take into account the existence of heterogeneous networks or the characteristics of traffic, and does not specify an operational method to split the traffic. Our work, on the other hand, accounts for all these aspects.

An analytical framework for allocation of services (e.g. voice and data) to multiple radio access technologies in order to maximize the combined multi-service capacity is presented in [13], and in [14] the authors examine algorithms for access selection by drawing a parallel with bin packing problems with the bins representing the access networks into which user services have to be packed. It is assumed in [13], [14] that the radio access networks are operated in a coordinated fashion. The suggested service allocation strategies represent a network-centric approach for resource allocation and do not touch upon technology specific implementation issues for executing the service allocation measures. Furthermore, the allocation of services to networks is static and is not dynamically varied according to varying network characteristics.

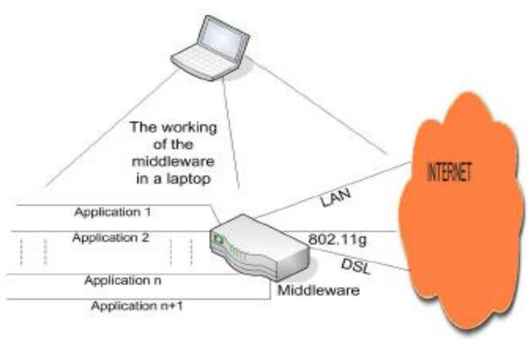

Fig. 1. Middleware functionality in a device work does not require any changes in or coordination between heterogeneous network access technologies that a device has access to, and suggests measures that can be employed by the device to dynamically assign traffic flows to the access networks.

Flow scheduling for collaborative Internet access in residential areas via multihued client devices is discussed in [15]. The scheduling framework proposed in the work only accounts for TCP flows and uses metrics useful for web traffic including RTT and throughput for making scheduling decisions. Our work on the other hand is generic and uses the stochastic characterization of networks and maximization of rewards offered by access networks to the flows with given utility functions for making flow scheduling decisions. We demonstrate the performance benefits of our flow assignment framework by employing elastic video flows with concave utilities.

The rest of this paper is organized as follows: We present the system model and analytical framework for flow assignment in Section II. In Section III, we describe measurement tests demonstrating heterogeneity in network characteristics. The performance evaluation of the flow assignment framework is presented in Section IV. A discussion on results and flow assignment in heterogeneous networks is presented in Section V, and the paper is concluded.

2. SYSTEM MODEL AND ANALYTICAL FRAMEWORK

Fig. 1 depicts the operational scenario for routing of flows originating from applications running on a device via access networks that the device has access to. The system components of the device include a *middleware* functionality that runs a lightweight tool to estimate the ABR and delay via different access networks to the destination hosts in the Internet. Applications running on the device consult the middleware for routing of flows. The list of preferred destinations hosts can be maintained at the device based on user usage history, user preferences, etc., as for instance described in [16].

We denote the set of access networks available to the device by I = {1, 2, . . . ,N}. The system state, designated as s S, represents the delay and ABR characteristics of all

3. NETWORK MEASUREMENTS AND MODELING

In this section we present results from network measurements conducted in a real world setting. Employing the modeling framework of the previous section, we will use the measurement traces to simulate and evaluate the flow assignment framework in the subsequent sections.

We conduct measurement tests in a corporate work environment where the users have access to networks like Ethernet, IEEE 802.11g and IEEE 802.11b WLANs, GPRS, and DSL.

We monitor the ABR and RTT on different networks between 2 PM and 4 PM on a work day. The tests are conducted between hosts in Deutsche Telekom Laboratories (T-Labs) in Berlin to three destinations - Stanford University, Technical University of Munich (TU Munich), and the Technical University of Berlin (TU Berlin) - respectively representing long, mid, and close distance destinations. We surveyed several publicly available tools including Pathrate, Nettest, CapProbe and choose Abing for measurement of ABR and round trip time (RTT). Abing has a fast convergence of the order of

seconds, is lightweight, and has the ability to run accurately on paths with high packet loss rates, and is hence reported to be suitable for wireless networks. It is based on packet pair dispersion technique and reports the ABR for bidirectional links between two hosts in the Internet which run Abing client and server.

Abing server is run at the machines at Stanford, TU Munich and TU Berlin, and the clients at machines in T-Labs in Berlin.

The ABR and RTT values are then noted every second for the links from T-Labs and to different destinations.

For the purpose of this work we consider the data collected on 100 Mbps Ethernet, IEEE 802.11g, and IEEE 802.11b networks. The 802.11g and 802.11b networks were accessed by laptops with Intel PRO/Wireless 2200 b/g cards through T-Sinus 154 and linksys WRT-54GL wireless access points (APs) respectively.

The test environment represented a well provisioned wireless LAN setting with 5 APs in a large office room. The measured networks had interference from other APs in the room and also APs from the higher and lower floors in the building. Tables I, II and III show the average ABR and RTT

TABLE I

AVAILABLE BIT RATE AND RTT FROM T-LABS TO TU BERLIN ABR(Mbps) RTT(ms)

		ABR(Mbps)	RTT(ms)
Ethernet	Avg.	71.8	5.2
	Std. Dev.	13.0	0.04
802.11g	Avg.	14.3	7.8
	Std. Dev.	3.6	0.4
802.11b	Avg.	4.5	10.7
	Std. Dev.	0.5	0.6

And their standard deviations to different destinations and for different networks for the 2 hour traces. Ethernet can be seen to have different ABRs to different destinations which can be attributed to different cross-traffic and intermediate bottleneck link capacities to these destinations. However, the average bit rates to different destinations are not much different for 802.11g and 802.11b indicating the possibility that ABR is constrained by the bottleneck wireless hop. RTTs to a destination are lowest for Ethernet and highest for 802.11b.

Figs. 3, 4, and 5 show representative histograms of the ABRs for the destination Stanford. The statistics can be seen to have diversity in ABRs across the three networks (the average ABR on Ethernet can be seen from Table I to be twice as much as on 802.11g which is roughly four times as much for 802.11b). All the networks display noticeable variation in ABRs. For instance the ABR on 802.11g can be as high as

24 Mbps and can drop down to as low as 6 Mbps.

The different ABRs on the networks reflect the difference in the ability of these networks in accommodating traffic flow volumes. Flows may be assigned to the networks according to their ABRs. However, as the characteristics of a given network fluctuate (for instance when there are abrupt drops in ABR), the supported applications may suffer from performance degradation.

Then, if some of the flows under adverse network conditions can be directed to another network, the performance of the applications and utilization of the networks can be improved. We will investigate this further in the Section IV.

We noticed that the scale of variation of ABR and delay was much greater for the wireless networks than for Ethernet, which justifies the use of MDP based stochastic modeling over a simpler approach when the access environment includes wired and wireless networks. For instance the average interval of variation of ABR by 10% was 10 times higher for 802.11b and 3 times higher for 802.11g than the ABR variation over Ethernet for T-Labs to Stanford case.

4. PERFORMANCE EVALUATION

We simulate the flow assignment framework using ns-2. The sample network topology created for the purpose is shown in Fig. 6. The node-S represents the sending device which sends flows to destination node-D via the networks N1, N2 and N3 using its middleware. We describe the functionality of the components and the tools employed below.

1) **Simulation of Access Networks:** Each network (e.g.
N1, N2, and N3 in Fig. 6) is simulated as a link with varying available bandwidth and delay characteristics.

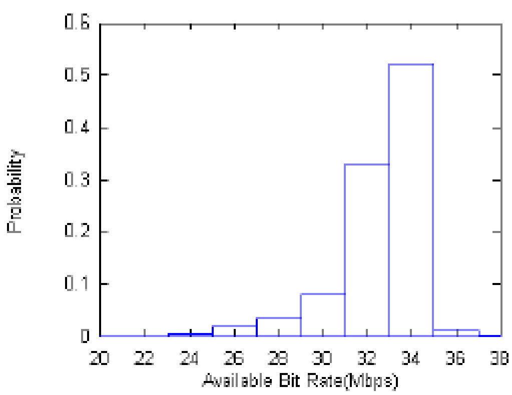

Fig. 3. Available bit rate on Ethernet from T-Labs to Stanford

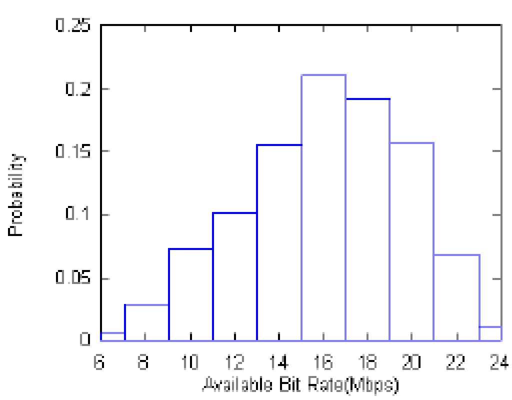

Fig. 4. Available bit rate on 802.11g from T-Labs to Stanford

These characteristics are obtained from the practical measurements performed in real networks settings - e.g. the ones described in Section III.

2) **Flow Assignment:** An instance of hash classifier [5] is attached to a node performing flow routing and is used to simulate a *broker* whose function is to direct various flows to different networks based on the policy calculated by the middleware. We implement part of the middleware functionality by interfacing python functions with ns-2. The middleware for a device measures the ABR and delay on the different networks, and performs the flow assignment using MDP. The flows at a node are identified via *flow id*s. We ensure that the broker agent attached to the node has information about every flow generated from the source and coming to the source

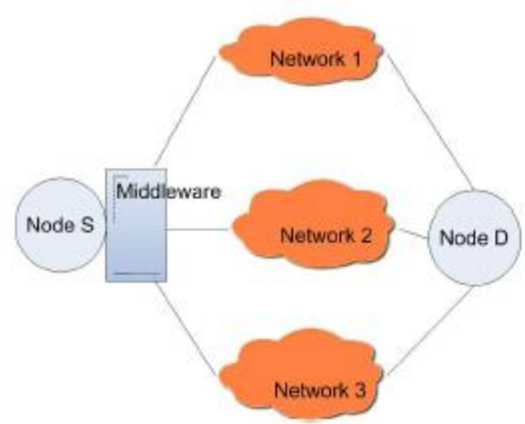

Fig. 5. Network topology in ns-2 from the Internet.

3) ***Network delay measurement:*** We employ CapProbe
Implementation for ns-2 to calculate RTT of networks. For this purpose, we attach a ping agent for every network to be monitored (e.g. N1, N2, N3 in in Fig. 6) to the node (e.g. Node-S) performing flow assignment and associate every ping agent with a flow id to be used by the hash classifier for routing the ping traffic.

4) **ABR Measurement:** The network bandwidth utilized at a given time is measured during the

simulation via queue monitors [5] attached to the links corresponding to the networks. The number of bytes transferred via the link during a 0.1 second interval is used to calculate the used bandwidth. ABR during the simulation is periodically evaluated by subtracting the network bandwidth being used from the present value of ABR used to characterize the network. In real world scenarios, tools like Abing can be used to measure ABR.

For the demonstration of evaluation results, the three networks shown in the ns-2 topology of Figure 6 are taken as Ethernet, 802.11g, and 802.11b with ABR (r) and delay (d) characteristics of Section III. The delay d is approximated as half of RTT values measured for different networks. Simulations are run over the 2 hour data traces for different destinations. For the 802.11b and 802.11g wireless networks we introduce a 1% random packet loss in the simulations.

We employ high bit rate flows with the characteristics of

Section II with rmin = 2 Mbps and T = 150 ms. At the beginning of a simulation, a total of 14 flows arrive with a rate of 2 Mbps each and an inter-arrival time of 0.5 seconds.

Subsequently the rates of the flows evolve as per the rate control associated with the employed flow assignment policy.

The middleware monitors ABR and RTT to the destination hosts via each network periodically.

For the greedy-AIMD policy, a flow upon its arrival is allocated to a network that offers the maximum instantaneous reward given by (2). For RP-AIMD, flows are allocated to networks in proportion to the average ABR reported in Tables I, II, and III. For both these static policies, the bit rate of each flow is varied according to a token-based roundrobin scheme where the token is circulated every 2 seconds.

5. DISCUSSION

Multiple network utilization via a flow allocation policy which stochastically characterizes the network characteristics and dynamically assigns flows to the networks results in significantly enhanced performance over a static policy which assigns flows based on heuristics like average ABR on the networks. Even in conjunction with a suitable rate control scheme, a static flow allocation policy suffers from degraded performance owing to the fact that network characteristics like ABR and delay vary to fluctuations in cross-traffic and changes in the channel characteristics for wireless networks.

A dynamic flow assignment policy is able to utilize the diversity of available networks to enhance the QoS provisioning for applications. For instance when ABR on a network drops or the delay shoots up, flows on the network may be reassigned to another network which may be experiencing a better network quality. An MDP based dynamical flow assignment presented in this work is demonstrated to result in better performance in terms of packet delays and packet loss rates experienced by applications, and bandwidth utilization for different networks.

We observed a tradeoff between selfish and global good as represented by the value of in (1). For low values of _representing a higher concern for characteristics of other interfaces than the one associated with the control action, the flows did not always drive the system to a state where they received a good reward on a network dictated by the control action, and this lead to bandwidth wastage. On the other hand, overtly selfish behavior (_=1) pushed the system into high delay states as the flows would eagerly choose a state that maximized their reward even if the state represented high delays and low ABR for the other interfaces.

A noticeable aspect is the ability of MDP based flow assignment to offer low packet loss rates while allowing the flows to have their share of bit rates on different networks. Other policies (RP-AIMD and greedy-AIMD) are unable to keep the packet loss rate within acceptable limits. Hence, the MDP based flow assignment can easily guarantee acceptable PSNRs for multimedia flows whose performance depends on the bit rate and the packet loss. Again, as the deadline for packet delivery becomes less stringent, the flow assignment policy results in a significant reduction in packet loss rates (Table VII).

6. CONCLUSION

In a setting where devices have access to multiple networks, the distribution of traffic flows amongst different networks can enable better network utilization than single network use at a time. However, the variation in network characteristics like ABR and delay make the problem of flow assignment challenging. A static flow allocation policy can result in unsatisfactory performance due varying characteristics of networks.

However, the adaptive assignment of flows to different access networks results in a much better performance in terms of packet losses, delays and allocated bit rates. Such adaptive flow reassignment can be done via stochastic characterization of the networks and adopting an MDP based approach to optimally assign flows to networks.

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