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Intelligent WiFi-offloading for Next-generation Mobile Networks

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Abstract

Mobile operators are leveraging WiFi access to relieve pressure on their cellular networks and offer faster data rates to meet the surging demand of applications. However in today's networks, operators either lack or have naive mechanisms to control the way end users access their WiFi networks. As operators deploy LTE networks that offer significantly higher data rates, intelligent traffic offloading to WiFi networks can enable operators to meet the rising traffic demand in a cost effective manner. In this regard, we design and implement `ATOM`*- an end-end solution for adaptive traffic offloading for heterogeneous WiFi and LTE deployments.* `ATOM` *consists of two novel components: (i) A practical network interface selection algorithm that maps user traffic across WiFi and LTE to optimize user QoE and (ii) an interface switching service that provides seamless redirection of ongoing user sessions to enable dynamic traffic management in a cost-effective and standards-compatible manner. We implement a prototype of* `ATOM` *on a real heterogeneous LTE-WiFi testbed and demonstrate its efficacy using both prototype evaluation and large-scale simulations.*

1. INTRODUCTION

Why Operator-WiFi? As mobile services gain popularity, recent years have witnessed an unprecedented increase in data traffic on cellular networks. While forecasts indicate an estimated average compound annual growth rate (CAGR) of 92% between 2010-2015 [1], the throughput increase per year due to technology improvements contribute to about 55%. As a result, although operators are continuously upgrading their networks, the growth in network capacity is considerably behind the growth in bandwidth demand. Hence, most operators around the world are aggressively deploying WiFi networks [2, 3, 4] to add capacity to their cellular networks. For instance, China Mobile has deployed over 3 million hotspots, AT&T in the U.S. has deployed approximately $30,000$ access points while KDDI has deployed over $100,000$ WiFi hotspots in Japan. Operators realize the value in WiFi since it offers high data rates and is cheap and easy to deploy at scale. As WLANs become a part of operators' network service offerings, a comprehensive end-to-end solution that manages the network interface (e.g., WiFi or Cellular) of user traffic flows forms a critical requirement of overall network optimization and management.

Drawbacks of Current Solutions: There are several distinct drawbacks of current interface management solutions, including those that are currently deployed in mobile networks: (i) *Naive and static policies*: Operators typically employ connection managers on the user devices to manage the flows over their cellular and WiFi networks. These connection managers are generally configured to select WiFi as the default interface when available [5]. Since WiFi APs are typically deployed in hot-spot areas to begin with, one can expect a large number of users to receive a strong signal strength from the WiFi APs during busy hours of the day. Hence such naive policies will not translate to better user throughput, since the load of the WiFi AP is not accounted for in the interface selection policy. Moreover, most operators do not have the capability to switch the interface of a flow seamlessly across WiFi and cellular; the interface selection decision is thus made when initiating the connection. Hence, the selection decision is not adaptive to the dynamic conditions of the wireless networks. (ii) *Coarse-grained policies:* The same level of throughput translates to different levels of QoE for a user depending on the application. Hence, loading all the application flows/sessions [6, 7] of a user on to the same interface does not translate to improved QoE for all the flows as the capacity of that interface has to be shared by multiple such flows from other users as well. (iii) *Lack of end-end solutions:* While some recent studies [7, 8, 9, 10] have focused on the problem of interface selection, they only solve a part of the problem. They simply provide algorithms for the interface assignment problem assuming a framework for seamless switching. Moreover, an end-end system encounters several practical constraints and challenges that it must account for to deliver a readily deployable solution. Thus, such naive and rigid nature of current interface management policies will diminish the potential effectiveness of WiFi as mobile data access increases.

Challenges: While the initial goal of operators was to leverage WiFi as a pure offload solution for their 3G networks; with the advent of 4G LTE networks that offer superior rates, a unified bandwidth management framework is critical to ensure good user QoE and effective use of wireless resources.

However, the desired attributes of such a framework are self-conflicting making the design of a practical system challenging: (i) to ensure that the framework is *practical*, it must be light-weight and scalable, but efficient; (ii) to ensure *high performance*, the system must dynamically adapt to flow arrivals, departures and changing link conditions of the clients. To be dynamic, the framework must be capable of seamlessly switching the interface of existing flows. However, this capability also poses a requirement to backhaul all the traffic from WiFi to the LTE network, thereby significantly increasing the operational costs. Thus, it is challenging to provide a dynamic solution given the lack of incentive for operators to invest heavily on user QoE for OTT (over-the-top) traffic. (iii) Finally, to ensure *deploy-ability* on current networks, the framework should be designed as an overlay solution over current 3GPP LTE standards. Thus, *the key challenge is to not just design a scalable, efficient and fine-grained traffic management solution, but to also build an end-end system that can be readily deployed as well as seamlessly integrated with any operator's core network (i.e. being operator agnostic) with minimal overhead*.

Our Approach: Towards meeting the above challenges, we present the design and implementation of `ATOM`- an end-to-end system that adaptively maps user flows to the appropriate network interface to improve user QoE, while being practical, efficient and cost-effective. Designed for next-generation LTE networks, `ATOM` incorporates two key components: (i) A traffic management solution that includes a practical yet effective algorithm for interface selection that operates at the granularity of application sessions. (ii) A switching service that seamlessly changes the network interface for ongoing user flows without the need for tight data plane integration. We observe that certain characteristics of HTTP-based video streaming and browsing can be exploited to enable seamless re-direction of flows across different network interfaces. By leveraging HTTP proxies and thus avoiding backhauling these traffic types from WiFi to the LTE network, `ATOM` offers an attractive low cost solution.

Implementation: We have implemented `ATOM` on a real-world heterogeneous LTE-WiFi network that mimics current network deployments. The LTE testbed consists of both the radio access and the mobile core network components with full 3GPP Release 9 functionality. `ATOM` is integrated with the LTE network to show the feasibility of deploying `ATOM` as an overlay over existing networks. Using real Internet traffic like YouTube, we provide extensive evaluation of improvement in user QoE with `ATOM` compared to scenarios that represent current networks. For instance, in presence of user mobility, `ATOM` was effective in reducing the stalls (or buffering periods) perceived by a user from an average of 8 to 2 per minute. In the same setup, the resource utilization of the LTE basestation was increased from 40 to 80% by `ATOM`. In addition, we evaluated the seamless interface switching functionality of `ATOM` with several video services like YouTube, Hulu, CBS etc. to demonstrate its feasibility in real networks and provide a link to a recorded demo. To the best of our knowledge, this is the first detailed design and implementation of a practical system that manages the traffic across LTE and WiFi networks applicable to current deployments. A noteworthy aspect of `ATOM`'s implementation is that it is operator-agnostic and standards-compatible, and can hence be readily deployed for any operator looking to manage its LTE and WiFi networks efficiently.

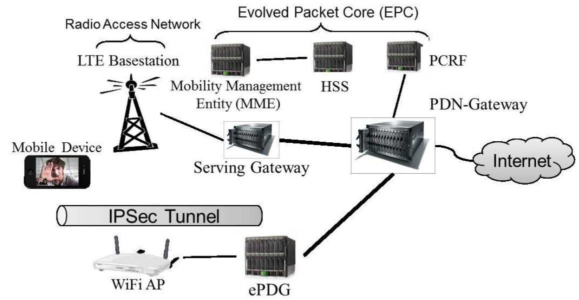


Figure 1: LTE Network Architecture.

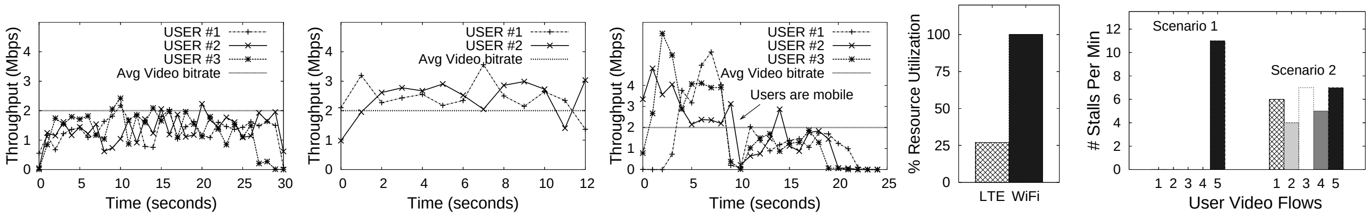
Contributions: To summarize, our contributions in this work are multi-fold: (i) We establish the hardness of the interface assignment problem and propose a two step greedy algorithm with performance guarantees under certain conditions. Our algorithm is simple, scalable and practical to implement. (ii) We design and implement an end-to-end system that seamlessly switches the interface for user flows to enable dynamic traffic management and (iii) `ATOM` is extensively evaluated using both large-scale simulations and several prototype experiments with actual Internet traffic.

2. BACKGROUND AND MOTIVATION

In this section, we give a brief overview of the LTE network architecture, then expand on the evolution of the integration of WiFi networks with LTE network deployments and motivate the need for an effective traffic management solution for LTE and WiFi networks.

2.1 LTE Networks

The top-half of Figure 1 shows a simplified 4G LTE network architecture, mainly consisting of two parts: the Evolved Packet Core (EPC) Network and the Radio Access Network (RAN). The EPC or the mobile core network consists of both the control and data plane functions. The control plane functionality is provided by the MME (Mobility Management Entity), HSS (Home Subscriber Server) and the PCRF (Policy and charging rules function). The MME handles session and subscriber management including user authentication, mobility management and idle terminal location management. The HSS includes a database that stores the user profile information while the PCRF manages the service policy and configures the QoS parameters for each user traffic flow. The data plane functionality in the EPC is split between the S-GW (Serving gateway) and the PDN-GW (Packet Data Network gateway). The S-GW acts as a local mobility anchor for user sessions as clients move across base stations.



(a)WiFi (Static) (b) LTE (c) WiFi (Dynamic) (d) Resource Util (e) Course-grained Policies

Figure 2: Limitations of Current deployments.

The PDN-GW is connected to multiple S-GWs and routes user traffic towards the external network, while also performing policy enforcement for resource management, packet filtering and charging functions. The RAN includes basestations (or eNodeBs) that perform radio resource management and interference mitigation.

2.2 WiFi Integration in Operator Networks

Several standard bodies such as 3GPP and WiFi Alliance (WFA) have defined standardized solutions for the network integration of LTE and WiFi. These solutions are mainly classified into two types: (i) *Access control*: To enable subscriber validation across the networks, seamless authentication and billing across LTE and WiFi networks is an important step to ensure WiFi integration. However, the method of authentication varies across operators. Most of the operators provide SIM based authentication [11] enabling them to maintain a unified subscriber database for both their LTE and WiFi networks. While other operators have adopted the traditional web-based authentication which requires the users to enter their credentials in the browser. (ii) *Data-plane integration*: To enable offloading capabilities and seamless mobility between LTE and WiFi networks, a tight data-plane integration is required across the networks. Such integration involves the backhauling of WiFi traffic to the LTE core network. Specifically, 3GPP has standardized the I-WLAN architecture [12] to integrate WiFi networks into LTE's mobile core network. The architecture as shown in Figure 1 enables the integration using the ePDG (evolved Packet Data Gateway), which serves as a gateway connecting the WiFi access point with the PDN gateway. IPsec tunnels are established between each mobile device and the ePDG, and the IP address is anchored at the PDN gateway. Since the IP address is maintained across the WiFi and LTE networks, flows can be seamlessly migrated across the networks. The PMIPv6 protocol is employed and the ePDG updates the IP address binding at the PDN gateway after authentication and tunnel establishment with the mobile device. Clearly, such tight integration will enable operators to ensure policy control, better QoE management and seamless mobility on their WiFi network as possible on their LTE network.

2.3 Current Deployments

In the near future, it is expected that operators will transition to using their WiFi networks for new services and revenue generation and provide better QoE for their users rather than just offloading for coverage or during congestion. Moreover, operators are quickly upgrading their network to LTE that offer superior rates than 3G networks and are deploying WiFi APs in areas of high network access. However, current deployments are not designed to use the LTE and WiFi network optimally to ensure good QoE for applications and users. Although most devices are pre-configured with connection managers, they mainly implement functions for network discovery, selection and authentication.

Short-comings: We bring to light a few key issues with current deployments through experiments on our LTE testbed and address them in the design of `ATOM`. The experiments are conducted using a network of a single LTE basestation and a WiFi AP within its coverage.

(i) Naive policies: Most connection managers [5] are configured with simple policies that ensure the device connects to a WiFi AP in case a connection is made. A few connection managers do ensure that WiFi AP is used only if the signal strength is above some threshold. However since they do not take the current load on the AP into account, the QoE of the users could suffer during congestion. To drive our point, we setup an experiment such that 6 users are randomly distributed and are within the coverage of the WiFi AP, while 2 users are outside the coverage of the WiFi AP. All the 8 users stream videos from YouTube with an average bit-rate of about 2 Mbps. We plot the throughput obtained by 3 out of the 6 WiFi users and the 2 LTE users in Figures 2(a) and (b) respectively. We see that the throughput obtained by WiFi users is less than the average bit-rate (2Mbps) of the video resulting in stalls in the video stream while the throughput of LTE users is above the average bit-rate resulting in a smooth stream. Figure 2(d) depicts the resource utilization: while the WiFi AP is over-utilized, the utilization of the LTE basestation is only 25%.

(ii) Static decisions: Moreover, it is not sufficient to make interface selection decision at the initiation of a user flow as wireless conditions change significantly due to user arrival/departure and mobility. To drive our point, we use a similar setup with 4 users on the WiFi AP. As shown in Figure 2(c), initially all the WiFi users receive throughput in excess of the video bit-rate. At around 10 seconds, we move a couple of the WiFi users away from the AP at walking speeds. As a result of the user mobility, the WiFi AP is unable to support the video rates of its users as shown in Figure 2(c) affecting the video of the users mid-stream. However, to enable dynamic traffic management, operators are required to poses the capability to switch the interface of user flows seamlessly across their LTE and WiFi networks. Such a capability needs tight data-place integration of the WiFi network with the LTE network. While the integration of access control (authentication) methods for WiFi have been widely adopted by operators [4], tighter integration of data or bearer plane to the LTE network has been resisted by most operators, mainly due to: (1) Backhauling large amounts of WiFi traffic through their LTE core network significantly increases both Operational costs (OP-EX) in terms of backhaul costs and Capital costs (CAP-EX) in order to scale their LTE core gateways. (2) Most of the traffic and services on mobile networks is OTT (Over-the-top) that does not generate direct revenue for the operators. Hence there is little incentive for operators to invest significantly in order to provide QoE for such services. (3) In most scenarios, we discovered that the WiFi business units of operators are managed independently from the LTE business.

(iii) Coarse-grained policies[6, 7]: Operators will desire the ability to perform interface selection on a per-application level rather than a per-user or per-device level. This capability ensures (a) operators can provide QoE depending upon the application requirements and (b) we envision that content providers will pay mobile operators for better QoE for users accessing their applications in the future. Operators will need to differentiate the performance of such flows over other OTT traffic. We conduct an experiment to show the disadvantage of the inability to perform fine-grained traffic management. The experiment is setup with 8 LTE users within the coverage of the WiFi AP and 4 LTE users outside the WiFi coverage. All the 8 users download a large file from the WiFi AP. One of the WiFi users (User#5) also streams a YouTube video of average rate 2Mbps. All the 4 LTE users stream the same YouTube video from the LTE basestation. Figure 2(e) plots the average number of stalls in the video session of the 4 LTE users and User#5. Scenario 1 represents the case where all the traffic of User#5 is mapped to the WiFi AP since the user is within the coverage of the AP. Clearly, the video flow of User#5 suffers significantly as the WiFi AP is congested. Scenario 2 represents the case with user-level traffic management where both the flows of User#5 (video and file-download) are moved to the LTE network. This results in the LTE network getting congested and the video of all the 5 users suffer. A fine-grained traffic management solution would include the ability to move the video flow of User#5 to LTE while keeping the file-download flow on the WiFi AP, resulting in good performance for the video of all the 5 users.

3. ATOM DESIGN

Accounting for the afore-mentioned drawbacks, we propose ATOM : an end-to-end operator-centric traffic management system that (a) enables operators to effectively manage user flows in a fine-grained manner across a heterogeneous cellular network comprised of LTE and WiFi APs to optimize (i) user QoE and (ii) network resource utilization; (b) includes a seamless interface switching framework that intelligently reduces the amount of backhaul traffic from WiFi in the LTE mobile core network thereby accelerating deployment. Before diving into the detailed design of ATOM, we explain some of the key design considerations:

(i) *Network vs Client*: ATOM is designed as a centralized network-driven solution for traffic management. This is more efficient resulting in better use of network resources as opposed to a pure client or connection manager based solution that runs as a distributed algorithm. Moreover, such distributed algorithms may require signalling from the network that violates standards compatibility and introduces additional overhead on the wireless link.

(ii) *Scalability*: Since traffic from an LTE cell (or base station) is offloaded to the WiFi APs that are within its coverage, ATOM is designed to operate at the level of an LTE cell i.e., each instance of ATOM manages user flows across a particular LTE cell and WiFi APs that are within its coverage. This ensures that the offloading solution is scalable and easies deployment as it can co-exist with existing inter-cell interference management techniques between LTE cells.

(iii) *In-network solution*: ATOM is a gateway-level solution that can be integrated with or deployed as a standalone middle-box within the LTE mobile core network as opposed to being deployed within each basestation. This design has the following benefits: (a) Typically middle-boxes such as deep packet inspection modules (DPIs), Policy engines (PCRF) etc. are placed within the LTE mobile core network and ATOM requires integration with these gateways to acquire appropriate information. Hence it is better to co-locate ATOM with these gateways. (b) Deploying ATOM in each basestation hinders deployability as it may require increase in computational capacity at the basestations.

(iv) *Granularity of operation*: To ensure that ATOM is adaptive to changing wireless conditions, it is executed periodically. However, ATOM is executed at coarse time-scales (several seconds) and decoupled from the basestation and access point MAC schedulers that are performed at fine time-scales (few milliseconds). This ensures that the traffic management algorithm is stable avoiding excessive switching of interfaces and is easier to deploy at a higher layer in the stack.

(v) *Pricing/Data Plans*: Operators around the world charge their users based on two plans: (i) Price per byte: Users are charged a fixed amount per KB of data (ii) Tiered data-caps: Users have a data usage limit (for eg. 3GB per month) based on a fixed monthly price. Moreover, operators offer WiFi service free of cost to their current customers. However, such a pricing model may change as operators promise similar carrier-grade service quality on their WiFi networks as they do on their LTE networks. As pricing plans continue to evolve, we design ATOM to incorporate general pricing mechanisms to ensure that its design is applicable for either of the

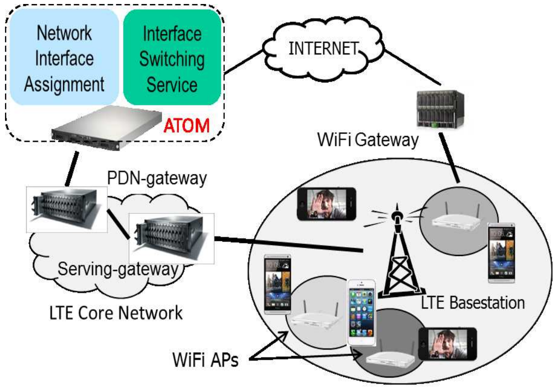


Figure 3: `ATOM`**'s Architecture.**

above pricing scenarios.

Drawing motivation from the above mentioned points, `ATOM` is instantiated as a gateway-level solution in the operator's access network external to the basestations as shown in Figure 3. Since the gateway will typically handle traffic for multiple basestations, it hosts multiple `ATOM` instances, each handling traffic for one basestation. `ATOM`'s design comprises of two components: (i) Network Interface Assignment (`NIA`) component and (ii) the Interface Switching Service (`ISS`).

4. NETWORK INTERFACE ASSIGNMENT

This is the component of `ATOM` that performs traffic management across all flows that belong to a given LTE cell. Specifically, it takes as input the signal strength of every user to its potential set of WiFi APs and the LTE basestation, relative QoS priority (or weights) and the current network interface of each user flow. It then computes the appropriate network interface (i.e., a specific WiFi AP or the LTE basestation) for each user flow. Since the goal of `NIA` is to maximize QoE for users, we must account for QoE variations across applications even for the same level of throughput. To capture such variations, the QoE of an application can be represented with the help of a per-application utility function for a user. Similar to typical resource management problems, we can formulate the problem of maximizing user QoE as a utility maximization problem that is executed periodically every T units of time:

$$\text{Maximize} \sum_{i=1}^{N} U_i(t_i)$$

where t_i is the average throughput for user flow i, N is the total number of active user flows in a given LTE cell and U_i is the utility function of flow i. The nature of the utility function determines the fairness model across user flows. We assume that the utility functions are concave, non-negative functions. Although such utility functions are suited for elastic traffic, recent advancements in adaptation of non-elastic traffic such as video delivery [13] enables us to treat the latter as elastic traffic as well. Maximizing the summation of the utility for each user flow ensures (a) optimal use of wireless resources from the operators perspective and (b) increased QoE from the users perspective.

Network Model: `ATOM` operates at the level of a LTE cell where one or more WiFi APs are deployed within the coverage of that LTE basestation as shown in Figure 3. `ATOM` is designed to handle scenarios where the coverage of several WiFi APs may overlap resulting in certain users having the option to connect to multiple WiFi APs. Hence, `NIA` computes the specific WiFi AP or LTE basestation that should be used by each user flow. Since `NIA` operates at coarse timescales (T is in orders of seconds), it leaves the fine-grained packet (MAC-layer) scheduling function to be performed by the LTE basestation and the WiFi APs locally. Hence, to allow this decoupling, the throughput is modeled as the average throughput received by the client over the time T based on the scheduling policy of the WiFi AP or LTE basestation. The problem can be formulated as:

$$x^* = \arg\max_{x} \sum_{j=0}^{B}\sum_{i=1}^{N} x_{ji} U(t_{ji}) \quad (1)$$

$$\text{subject to} \quad \sum_{j=0}^{B} x_{ji} = 1$$

where B is the total number of WiFi APs within the coverage of the LTE basestation (represented by $j = 0$). The indicator variable $x = \{x_{ji}, \forall j\}$ denotes the association vector for all the user flows i.e., $x_{ji} = 1$ if user flow i is assigned AP j. t_{ji} is the average throughput estimated for user flow i when associated with the AP j. The constraint ensures that exactly one WiFi AP or LTE basestation is chosen for a user flow. Different flows of a user are allowed to pick potentially different WiFi APs. In practice, this can be realized using the virtualization capability found in most WiFi cards to create multiple virtual WiFi networks that can be run on a single WiFi physical interface [14]. The challenge in solving the above optimization lies in the utility (and throughput) function that couples the decisions of user flows assigned to the same interface.

Throughput and Fairness Models: LTE and WiFi have different medium access (MAC) protocols and can potentially employ distinct fairness (bandwidth sharing) policies across the user flows that directly affects the throughput obtained by the user flows.

LTE basestations typically perform proportional fair scheduling across the user flows. Moreover, a LTE basestation schedules the resources to the user flows in proportion to a weight that defines the relative priorities of the flows. In this case, the achieved throughput of a user can be shown to depend on the total number of the other users as well as their relative weights as follows.

$$t_{ji} = \frac{w_i \times r_{ij}}{\sum_{i \in N_j} w_i} \quad \forall i \in N_j \quad (2)$$

where w_i is the weight for user flow i; r_{ij} is the average link-layer rate (or the PHY rate) of user i on AP j (LTE BS in this case) depending on the average signal-to-noise ratio (SNR) of the user on that AP and N_j is the total number of active users on AP j.

On the other hand, WiFi networks when operated distributively, typically employ a throughput-based fairness model. Here, all the users connected to the same AP typically achieve the same throughput at steady state. This is because the APs typically implement a round-robin scheduling scheme for the downlink packets. In this case, the average downlink throughput of a WiFi user can be expressed as:

$$t_{ji} = \frac{L}{\sum_{i \in N_j} \frac{w_i L}{r_{ij}}} \qquad \forall i \in N_j \tag{3}$$

where L is the average size of a packet in bits.

However, when the operator controls both the LTE and WiFi networks, then it is possible to instrument a uniform fairness policy (say proportional fairness) across both these networks. In this case, the throughput of users in the WiFi APs would follow a throughput model similar to that for LTE. Also, we assume that interference between neighboring LTE cells and WiFi APs is taken care of through their respective interference management algorithms (frequency reuse algorithms in LTE and channel selection in WiFi), so as to not affect the throughput models.

Choice of Utility Function: While our algorithms would work with concave utility functions in general, for performance evaluation and guarantees, we adopt a logarithm function as the utility function, owing to its popularity in resource management for wireless networks [15, 16].

$$U(t_i) = \log(t_i) \tag{4}$$

Such a utility function ensures that the marginal utility of a flow decreases as the throughput increases. Also, when both LTE and WiFi implement proportional fair scheduling, this would automatically result in maximization of the aggregate utility functions of all the flows.

Pricing Model: The notion of pricing the different interfaces based on their consumption can be easily incorporated in our utility framework as well as our algorithms. The utility of an interface assignment for a user flow i can be updated as $(U(t_{ij}) - E_{ij})$, where E_{ij} is the associated cost for flow i using the interface j and is defined based on the pricing model of the operator: (i) *Pricing per byte*: E_{ij} can be made to capture consumption in the current epoch as $E_{ij} = C_j w_i$ [8], where C_j is the cost per unit weight of the flow. Since the actual throughput delivered to a flow in an epoch depends on multiple factors, the cost is typically based on the weights [8], which influences how throughput is shared. (ii) *Tiered Data-caps*: On the other hand, E_{ij} can capture data usage till the previous epoch as $E_{ij} = C_j \frac{D_{kj}}{n_k}$. C_j would now be the cost per unit KB of data (given by dividing the data cap of the user by the monthly cost of the plan), D_k is the total data usage till the previous epoch by user k on network j, and n_k is the total number of flows at user k, thereby splitting the cost of a user equally across all its flows. Hence, the associated cost of an interface E_{ij} is higher for the flows of the users with higher data usage in the past on that interface. Instead of a linear function, one could also consider other functions of data usage.

An important point to note is that the pricing is mainly used to serve as a deterrent in picking an interface. By appearing as a constant in a given epoch, it does not directly influence the per-epoch optimization problem.

4.1 Problem Hardness

Considering even the simplest topology with one LTE basestation and a single WiFi AP, the complexity for solving the problem grows exponentially with the number of user flows. Intuitively, the problem is hard because the correct choice of a network interface for a given user flow depends on the exact combination of other user flows assigned to the APs. Specifically, in the case of WiFi AP, the throughput achieved by a user flow depends on the PHY rates of the other users attached to the AP (throughput fairness) and in the case of LTE, the throughput achieved by a user flow depends on the weights of the other users attached to the basestation (Refer to Equations (2) and (3)). The complexity of the problem further increases when considering the case with multiple WiFi APs within a LTE cell, especially the case where some of the APs may have overlapping coverage. Hence, it can be easily shown that the problem is NP-Hard.

4.2 Algorithm

`NIA` proposes and employs a practical and simple yet efficient greedy algorithm. The algorithm is executed in two steps as shown in Algorithm 1. It takes as input the number of active user flows N, the number of WiFi APs B within the LTE cell and the subset of user flows N_j that are within the coverage of the WiFi AP j. Also note that the sets N_j may not be independent since certain users may be covered by more than one WiFi AP. Initially all active user flows that are not within the coverage of a WiFi AP are assigned to the LTE basestation (i.e., $A_0 \leftarrow N_0$). π represents the set of all the WiFi APs whose users have not been assigned an interface yet and L_j represents the set of user flows that belong to a WiFi AP's coverage but have not been assigned an interface yet (i.e., $L_j \subseteq N_j$).

In the outer loop at every step, `NIA` considers each WiFi AP, whose user flows remain to be assigned an interface, in isolation. It computes the best combination of user flows across the LTE cell and a particular WiFi AP. It then finalizes the interface assignment for all the user flows of that WiFi AP, which yields the highest utility among all the WiFi APs (step 18). Having fixed the interface assignment for user flows of an WiFi AP in a single round, the initial condition is reset with this assignment. Specifically, the WiFi AP for which the interface assignment is finalized is removed from the set π (Step 19). The user flows that are assigned to an interface are removed from the set L_j of the other WiFi APs (Step 20) that also cover these flows so that they are not considered in the following rounds. The user flows assigned to the LTE basestation are added to the set A_0 (Step

21). The computation steps are repeated for each of the remaining WiFi APs until the user flows of all WiFi APs have been assigned an interface. As discussed above, since the assignment of user flows to LTE basestation and a single WiFi AP is also computationally complex, `NIA` employs a greedy algorithm to compute the assignment in the inner loop (steps 8-17).

The inner loop performs the assignment of user flows for each pair of WiFi AP (whose flows have not been assigned an interface yet) and the LTE basestation. Initially, no user flows are assigned to the WiFi AP (Step 9). The assignment for the LTE basestation (Step 10) is initialized with the user flows that are already assigned to LTE (A_0) and the unassigned user flows that are within the coverage of the WiFi AP j (L_j). Starting with these initial assignments, `NIA` moves user flows one by one from the LTE basestation to the WiFi AP such that the incremental utility is maximized. For each user flow, the incremental utility is the difference in utility with the current interface assignment (i.e. LTE) and the interface assignment with the user flow moved to the WiFi AP (Step 12). `NIA` stops moving user flows from LTE basestation to the WiFi AP when none of the remaining user flows result in a positive increase in the marginal utility. After this step, `NIA` commits the utility for the particular WiFi AP as shown in step 16.

Algorithm 1 `NIA` Algorithm

1: INPUT: $\forall i \in \mathcal{N}$ (# of Active user flows),
$\forall j \in \mathcal{B}$ (# of WiFi APs), $\mathcal{N}_j \subseteq \mathcal{N}$ (# of Active user flows within the coverage of AP j.
2: OUTPUT: User flow Association $\mathcal{A}_j, \forall j \in \mathcal{B}$
3: $\pi \leftarrow \{B\}, \mathcal{A}_0 \leftarrow \{N_0\}$
4: $\mathcal{L}_j \leftarrow \{N_j\}, \forall j \in \mathcal{B}$
5: % Outer Loop
6: **for** $x \in [1 : |\mathcal{B}|]$ **do**
7:   % Inner Loop
8:   **for** $j \in \pi$ **do**
9:     $\mathcal{A}_j = \emptyset$
10:     $\mathcal{A}_{0j} = \mathcal{A}_0 \cup \mathcal{L}_j$
11:     **for** $i \in \mathcal{L}_j$ **do**
12:       $i^* = \arg\max_{(i) s.t.\ i \notin \mathcal{A}_j} \{\sum_{k \in \mathcal{A}_j \cup i} U(t_{jk}) + \sum_{k \in \mathcal{A}_{0j} - i} U(t_{0k}) - \sum_{k \in \mathcal{A}_j} U(t_{jk}) - \sum_{k \in \mathcal{A}_{0j}} U(t_{0k})\}$
13:       $\mathcal{A}_j \leftarrow \mathcal{A}_j \cup i^*$
14:       $\mathcal{A}_{0j} \leftarrow \mathcal{A}_{0j} - i^*$
15:     **end for**
16:     $U_j = \sum_{i \in \mathcal{A}_j} U(t_{ji}) + \sum_{i \in \mathcal{A}_0} U(t_{0i})$
17:   **end for**
18:   $b \leftarrow \arg\max_j U_j$
19:   $\pi \leftarrow \pi - b$
20:   $\mathcal{L}_j \leftarrow \mathcal{N}_j - \mathcal{A}_b, \forall j \in \mathcal{B}, j \neq b$
21:   $\mathcal{A}_0 \leftarrow \mathcal{A}_{0b}$
22: **end for**

4.3 Performance Guarantee

Given the complexity of the problem in the general case, it is hard to claim a worst-case performance guarantee for our algorithm, although its average-case performance in evaluations is very efficient. However, interestingly, under certain cases, it is possible to compute an optimal solution through

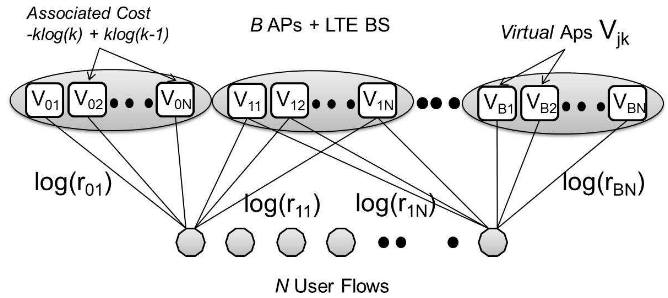


Figure 4: Illustration of user flow assignment

a novel transformation. Specifically, we have the following result.

Theorem 1 *When the weights of all the user flows are unity and both LTE and WiFi employ proportional fairness, the problem is optimally solvable.*

PROOF. The proof involves a novel transformation to an equivalent assignment problem.

Since we are considering proportional fairness with unity weights for the user flows, the optimization problem reduces to,

$$\text{Maximize} \qquad \sum_{j=0}^{B} \sum_{i=1}^{N} x_{ji} \log(t_{ji}) \qquad (5)$$

$$\text{subject to} \sum_{j=0}^{B} x_{ji} = 1, \quad \text{and} \quad t_{ji} = \frac{r_{ji}}{|N_j|} \qquad \forall i \in N_j$$

Thus, we need to assign the different user flows to the WiFi APs and the LTE basestation, so as to maximize the aggregate system utility. Consider the following transformation to an assignment problem: for every AP j, create N virtual APs V_{jk} (to accommodate up to N user flows per AP), where $k = [1, N]$, thereby resulting in a total of BN virtual APs (VAPs). Now, every VAP V_{jk} is associated with a cost $-k\log(k) + (k-1)\log(k-1)$. When a flow i is assigned to a VAP V_{jk}, its net utility is the sum of two terms: (i) the logarithm of its rate at that AP (i.e. $\log(r_{ji})$) and (ii) the associated penalty, i.e. $U_{jki} = \log(r_{ji}) - k\log(k) + (k-1)\log(k-1)$. This is illustrated in Figure 4. Now, finding a maximum weight matching (assignment) in this bipartite graph (between the user flows and the virtual APs) directly solves the above optimization problem, for which algorithms like the Hungarian or auction-based algorithms can be employed.

Although unity weights for clients removes direct coupling of utilities between user flows assigned to the same AP, a flow's utility still depends on *the number of flows* assigned to the AP in the form of a penalty ($-\log(|N_j|)$). The latter, however is an output of the assignment problem. If one looks at the transformation carefully, one will observe that this penalty is distributed among the N VAPs belonging to the actual AP. However, being an assignment problem, only certain edges will be selected as part of the solution and the challenge is to ensure that the distribution of penalty is made such that the final penalty for an AP reflects the exact number of flows assigned to that AP.

Our penalty distribution precisely achieves this objective. To see this, first observe that $k\log(k) - (k-1)\log(k-1)$ is a monotonically increasing function (indeed it can be shown to be sub-modular) and so is the penalty. Hence, if a flow i is assigned to a VAP k at AP j, with an earlier VAP k' being un-assigned, then flow i can always be re-assigned to k' to increase its utility (user's rate does not change between VAPs at an AP). In other words, if VAP k is the last assigned VAP at an AP, then all VAPs until k would have been assigned at the AP. Thus, VAP assignment at an AP will always be *contiguous* under our penalty function. Now, the net penalty required when k VAPs are assigned at an AP is always $k\log(k)$, which is automatically obtained when the individual penalties of the VAPs are aggregated in a contiguous manner.

$\square$

5. INTERFACE SWITCHING SERVICE

The goal of the ISS framework is to provide a service to the NIA to enable dynamically switching the interface or network of user flows to ensure effective traffic management. Every T seconds based on the decisions made by the NIA, the ISS switches the network for the appropriate user flows. The fundamental problem in providing seamless connectivity across networks is maintaining the end to end TCP connection since the IP address of the user changes. While standard bodies like 3GPP adopt the approach of maintaining the same IP address by anchoring all the traffic through a common gateway, ISS takes a different, yet seamless and low-overhead approach based on two key observations: (i) Mobile operators are resisting tight integration of the data planes of their LTE and WiFi networks to avoid significant increase in backhauling costs for the WiFi traffic (as discussed in Section 2). (ii) HTTP is the dominant mobile protocol (over 90% traffic carried over HTTP [17]). More importantly, HTTP-based video traffic accounts for more than 60% of the total bytes carried on mobile networks and is expected to increase to more than 75% [18]. Although UDP protocol is more suited for video streaming, HTTP/TCP protocol has been employed widely to leverage existing benefits of HTTP, namely caching, CDNs, traversal through NAT, content naming etc. Keeping the above mentioned observations in mind, ISS intelligently leverages certain characteristics of HTTP-based video streaming and web-browsing (discussed below) to design a switching service that switches network interface of flows without anchoring the connection through a single gateway, thereby avoiding backhauling of WiFi traffic through the LTE core network.

5.1 Quick Primer on HTTP

Traditionally HTTP-based video streaming used to be treated like a file download. However, with recent advancements, two popular schemes are employed for HTTP based video streaming: (i) HTTP progressive download(PD): In this scheme, video players typically request the video in byte ranges instead of downloading the entire video file. HTTP-PD was introduced to ensure video pacing i.e., the client can request chunks of videos at a download rate that matches the playing rate and avoid wasting bandwidth in case the user quits the player before the video ends. HTTP-PD also allows users to seek to a later point in the video. (ii) Dynamically adaptive streaming over HTTP (DASH): The design of DASH [13] is aligned with HTTP-PD, however it allows the player to request different encoded versions of the video ensuring adaptability to the network conditions. As shown in Figure 5, the original video is encoded into multiple bit-rates and chunked into segments or chunks that typically contain 4-10 seconds of video. Initially, the player downloads a MPD file containing the URL for each chunk for every encoded version of the video. Periodically, the player sends HTTP-GET requests to the server to download the chunk of the appropriate bit-rate according to measured TCP throughput. Similarly, web or browsing traffic typically consists of several relatively small sized objects (e.g., html, css, js, images etc.) wherein each object is requested by an individual HTTP-GET request.

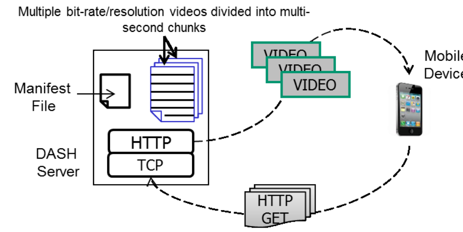


Figure 5: DASH Video Delivery.

5.2 Leveraging HTTP

The ISS framework leverages the above characteristics of HTTP-based video streaming and browsing wherein the content within a session is downloaded using multiple HTTP GET requests over time. Specifically, when the interface or network of these flows have to be switched, subsequent HTTP-GET requests of these flows can be performed over the new interface. Although, typically HTTP-GET requests are multiplexed over existing TCP connections, sending HTTP requests over multiple TCP connections in parallel is supported by HTTP. Hence, the subsequent HTTP-GET requests are made over one or more TCP connections that are set up over the new interface or network. Although this applies only to HTTP-based video streaming and browsing flows, these traffic flows do not need to be backhauled to the LTE network, thereby saving significant costs for the operator. This is especially important, given that video traffic accounts for a sizeable portion of the total bytes carried by mobile networks and web traffic is the most popular traffic type.

5.3 Design of ISS

ISS is designed using HTTP proxies in the LTE network and a HTTP proxy at the mobile device to enable seamless interface switching on existing mobile networks as shown in

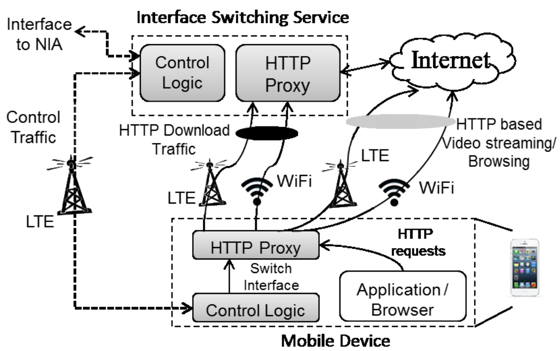


Figure 6: Interface Switching Service.

Figure 6. The HTTP proxy on the mobile device ensures that the HTTP requests from the applications or browser are sent over the appropriate interface. The applications and the browser on the mobile device are configured to use the *HTTP proxy* on the device. This ensures that all HTTP traffic generated from the device is routed through the HTTP proxy on the device. The HTTP proxy is a light-weight user-space program that is capable of proxying the HTTP request from the application or the browser to either the network proxy or directly to the content servers. The HTTP proxy listens for commands to switch interfaces from the *Control Logic* on the device. Similarly, on the LTE network-side the ISS framework consists of a HTTP Proxy and a Control Logic. The Control Logic exposes an interface for the NIA to send commands for switching the network interfaces of user flows based on the output of the algorithm. The network-side Control Logic maintains a persistent TCP connection with the Control Logic on every device through the LTE network to relay the commands from the NIA to the appropriate devices as shown in Figure 6. The HTTP Proxy within the LTE network is employed for HTTP traffic that excludes video streaming and browsing to ensure seamless switching for other types of traffic. Most mobile operators already deploy HTTP proxies for optimizations and caching purposes.

The specific procedure of the switching functionality executed by ISS depends on the traffic type of the user flow:

1. HTTP-based downloads: These traffic flows may include downloading of medium to large-sized files (e.g., Dropbox), software updates, application downloads etc. To ensure that such flows can be seamlessly switched from LTE to WiFi network or vice versa, these flows are always routed through the in-network HTTP proxy as shown in Figure 6. Routing the HTTP traffic through the same proxy for both LTE and WiFi networks ensures that the flow is anchored at a single server, and can be switched seamlessly across the networks. Specifically upon receiving the command to switch interfaces from the ISS, the HTTP proxy on the device sets up a TCP connection with the network HTTP proxy using the new interface. The network HTTP proxy tears down the TCP connection over the current interface before sending data over the new TCP connection to keep the HTTP session alive.

2. HTTP-based video streaming and browsing: Unlike the previous traffic type, switching is performed differently for video streaming and browsing traffic. Specifically, these flows are not routed through the in-network HTTP proxy as shown in Figure 6 avoiding backhauling traffic from WiFi to the LTE network. After receiving a command from the control logic to switch the network interface for a specific web session, the HTTP proxy on the device simply requests the subsequent objects from the new interface, while continuing to receive existing objects from the current interface. In a similar fashion, for video flows, upon receiving the command to switch interfaces from the control logic, the HTTP proxy in the device simply requests the subsequent chunks of the video from the new interface.

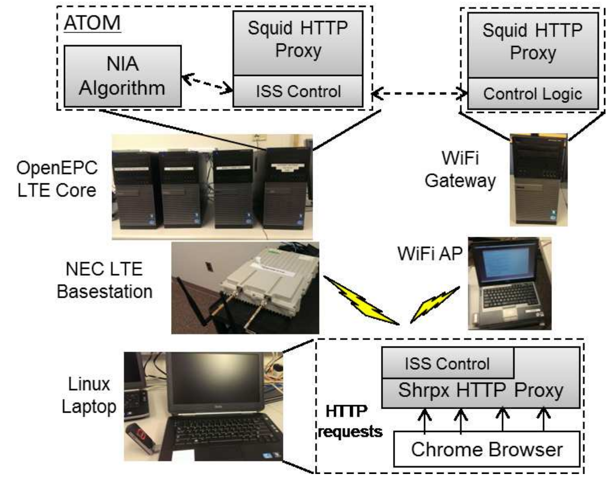


Figure 7: ATOM Prototype.

By leveraging and instrumenting HTTP proxies, ATOM is able to realize a seamless, operator-agnostic interface switching service that can be readily deployed. Further, with video traffic not requiring an in-network HTTP proxy, ATOM is able to avoid backhauling the bulk of the traffic (being video) from the operator's LTE core network as well.

6. PROTOTYPE

In this section we describe our prototype implementation on a heterogeneous LTE-WiFi testbed. We also recorded a video demo (link available on project page [19]) of our testbed to show the efficacy of ATOM.

6.1 Test-bed

Our prototype consists of a NEC LTE basestation (or eNodeB) [20], openEPC software based LTE mobile core network [21], Madwifi-based WiFi access point and Linux laptops as clients that house both Verizon Pantech LTE dongles [22] and Broadcom WiFi cards (see Figure 7) deployed indoors in our Lab. The NEC LTE basestation is 3GPP Release 9 compliant small cell prototype base station which operates in the 700Mhz band (Band-13). Considerable effort, involving code modifications to the openEPC components, was spent to integrate the basestation with the openEPC network to ensure complete functionality such as connectivity and data transfer with commercially available LTE clients.

The various components of openEPC are implemented as C modules. In our setup, we run the openEPC components over four Intel-based servers such that certain components share the same machine as shown in Figure 7. This limited resource provisioning is sufficient since we run only a small number of flows in our experiments. Our EPC network [21] consists of various components like MME, HSS, PCRF for control plane functions and S-GW and PDN-GW for data path routing. In addition, the Internet gateway provides connectivity to the Internet and includes key functions like NAT, DNS etc. The client devices we use are primarily Pantech USB dongles that operate on Band-13. We use USIM cards obtained from Sysmocom [23] programmed with the appropriate identification name and secret code to ensure connectivity with the LTE network testbed. Since the LTE basestation and clients are configured to transmit on the Verizon frequency, we use custom built frequency converters. The frequency converters are connected to both the basestation and the USB dongles and convert the frequency in both downlink and uplink from 700Mhz to 2.6Ghz, where we have an experimental license to conduct over the air experiments. The testbed also consists of a Madwifi-based software WiFi AP with Atheros cards and a Ubuntu machine that acts as the WiFi gateway.

6.2 Implementation

Network: The components of ATOM are implemented on the Internet gateway that connects directly to the PDN-gateway of our LTE network. NIA is implemented within the Click modular router framework using C++ code, while the ISS-control is implemented as a standalone C++ application. A well-defined interface is implemented between the NIA and the ISS. NIA periodically gathers the following information from ISS (a) number of user flows active on LTE basestation and WiFi APs, (b) current interface used by each flow (c) priority/weights of application flows and (d) link-layer or PHY rate of each flow. A control logic component is also implemented within the WiFi gateway that provides information about active user flows over the WiFi APs and the link-layer rate of each WiFi user (collected from the APs) to the ISS-control. Once the NIA gathers all the information in an epoch, it executes the algorithm to compute the network interface assignment for each flow and sends a message to the ISS-control with information about all user flows that need to be switched to a new network interface. The prototype also includes two Squid [24] HTTP proxies in the network side for both LTE and WiFi networks.

Client Device: On the device, we implement the ISS-control framework within the Shrpx based HTTP proxy software module [25] that runs as a user-space process. We chose Shrpx as it is open-source, can be deployed in multiple configurations, supports multiple protocols and can be cross-compiled for Android. The Chrome browser is configured using the PAC (Proxy Auto-Configuration) file to use the Shrpx proxy as the default proxy for all applications. Hence, all the HTTP requests from the Chrome browser are made to the Shrpx proxy. Initially when the device comes online, the ISS-control on the device establishes a persistent TCP connection and registers using a unique ID with the ISS-control on the network side. When a new application flow is initiated, the Shrpx proxy always connects using the WiFi network if available. In the case of *HTTP-based download* flows, the connection is always made to the Squid proxy on the LTE network to ensure seamless mobility. Upon receiving a command to switch the network interface to LTE from ISS-control, the Shrpx proxy establishes a new TCP connection with the Squid Proxy through the LTE network. The Squid proxy then terminates the previous TCP connection over WiFi, before sending HTTP data over the LTE network to ensure seamless continuity of the HTTP session. On the other hand, in the case of *HTTP-based video streaming or browsing* flows, the initial connection is made to the Squid proxy on the WiFi network avoiding backhauling traffic through the LTE network. Upon receiving a command to switch network interface to LTE from the ISS, the Shrpx proxy establishes a connection with the Squid Proxy on the LTE network and relays all new HTTP requests from the browser through the LTE network. The Shrpx proxy breaks the TCP connection with the Squid proxy over the WiFi network after all the pending HTTP requests have been downloaded. For both traffic types, the same procedure is repeated when a connection has to be switched to WiFi from LTE.

Currently, we employ SPDY [26] as the protocol between Shrpx and the Squid proxies. Although the network (both LTE and WIFI) proxies are not required for HTTP-based video streaming or Web browsing traffic types, it is employed in our prototype since Shrpx is currently not designed to connect to multiple servers. Since most Web servers require multiple simultaneous TCP connections, Shrpx is configured to relay the HTTP requests to the respective Squid proxy based on the current network interface used by the device. An important aspect of our implementation is that it can be readily deployed by instrumenting existing mobile protocols and is completely standards compatible, while also being operator-agnostic.

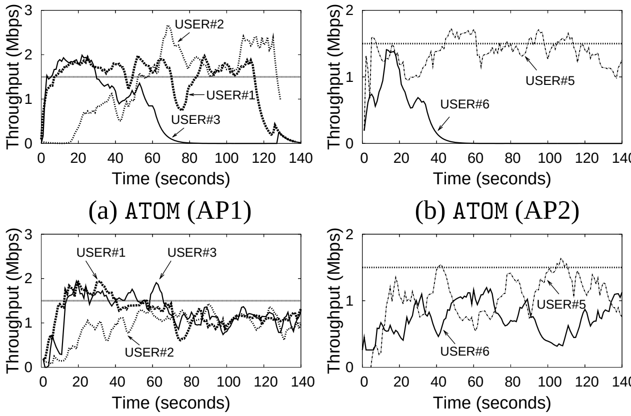
Execution flow: In summary, the high-level execution flow in the current design of ATOM involves the following steps: (i) User flows always initiate the connection from WiFi AP if available and register with the ISS in the network; (ii) NIA executes periodically to make interface selection decision for all active user flows and (iii) NIA sends a command to the ISS consisting of user flows with new interface information.

7. PERFORMANCE EVALUATION

In this section, we demonstrate the efficacy of ATOM using experiments on our LTE prototype as well as through large-scale simulations.

7.1 Prototype Evaluation

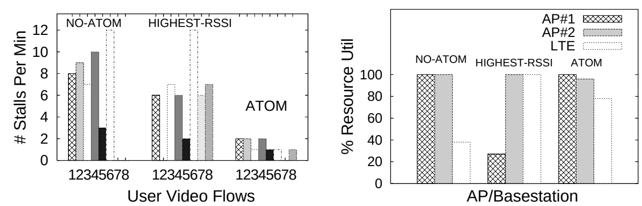
We consider two types of workloads including video stre-



(a) ATOM (AP1) (b) ATOM (AP2)

(c) NO-ATOM (AP1) (d) NO-ATOM (AP2)

Figure 8: ATOM ensures good throughput.



(a) Stalls (b) Utilization

Figure 9: ATOM ensures high QoE and network util.

aming from YouTube and HTTP based file downloads. We demonstrate the efficacy of ATOM using metrics such as throughput measurements and number of stalls due to buffering in the video streams. For TCP-based videos, number of stalls is representative of the user satisfaction. NO-ATOM represents the current deployment scenario that maps user flows to WiFi APs if the user is within the coverage of a WiFi AP.

1) Static Experiment: We setup an indoor network of LTE basestation and two WiFi APs with a total of 11 users in the cell, such that 5 users are within the coverage of WiFi AP1, 4 users are within the coverage of WiFi AP2 and 2 users can only access the LTE basestation. WiFi AP1 is placed closed to the LTE basestation while WiFi AP2 is placed further from the LTE basestation and all the users are distributed randomly. In WiFi AP1, 4 users steam YouTube videos of average bit-rate 1.5Mbps while 1 user downloads a large-file. In WiFi AP2, 2 users stream YouTube videos of average bit-rate 1.5Mbps while 2 users download large-files. Both the LTE users stream YouTube videos of average bit-rate 1.5Mbps. We compare the throughput received by the WiFi users for the case with and without ATOM (NO-ATOM).

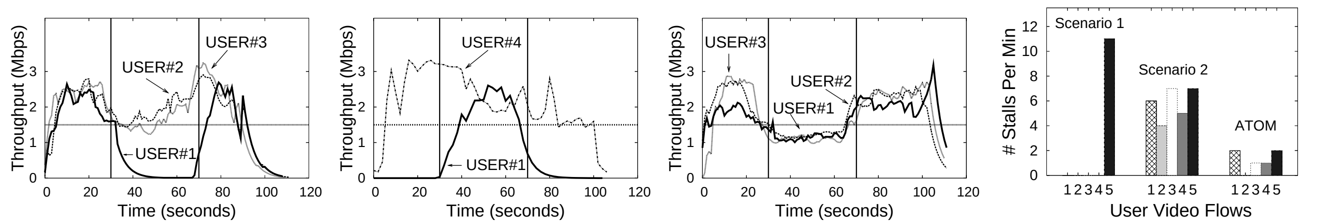
Figure 8(c) and (d) plots the throughput for 3 video streaming flows on WiFi AP1 and 2 video streaming flows on WiFi AP2. Clearly, the throughput obtained by the user flows cannot be sustained to meet the average bit-rate of the video since both the APs are congested. On the other hand, ATOM ensures that flows of Users#3 and 4 from WiFi AP1 and User#6 from WiFi AP2 are moved to LTE basestation to ensure that the throughput received by all users meets their requirement of 1.5Mbps. Figures 8(a) and (b) plot the throughput received by the users on the WiFi AP1 and 2 respectively. Hence, by effectively distributing user flows across LTE and WiFi APs, ATOM improves both (i) *User QoE*: As seen clear from Figure 9(a), ATOM decreases the number of stalls perceived by users from an average of $8-10$ stalls per minute with NO-ATOM to atmost $1-2$ stalls per minute. (ii) *Network Utilization*: ATOM also improves the resource utilization of the LTE basestation from 40% to almost 80% as shown in Figure 9(b).

We also conducted the same experiment for another case where the user device selects the interface depending upon the highest signal strength, represented as Highest-RSSI. In this scenario, most of the users of WiFi AP1 (Users#1,3 and 4) select the LTE basestation while users of WiFi AP2 chose WiFi since users of WiFi AP2 are placed further from the LTE basestation than those of WiFi AP1. Hence, this scenario results in congestion in the LTE network resulting in high number of stalls for all users including Users#7 and 8 that can only connect to the LTE basestation (refer Figure 9(a)). Although this scenario improves the utilization of the LTE basestation (Figure 9(b)), the overall network utilization is lower than ATOM as WiFi AP1 is heavily under-utilized. Hence, even in static conditions, current solutions cause severe degradation in user QoE and network under-utilization, strengthening the need for a solution like ATOM.

2) Network Dynamics: We conduct a few experiments to show the efficacy of ATOM with network dynamics:

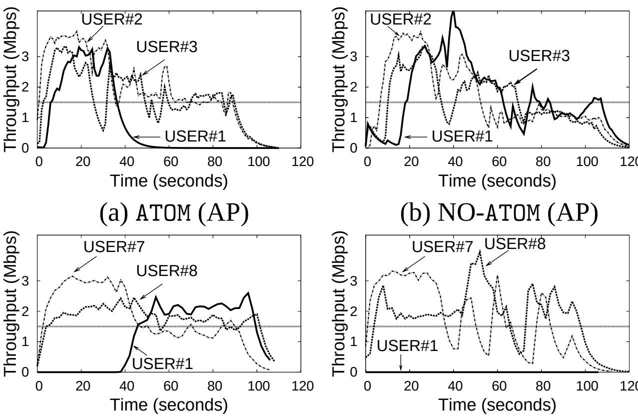
(i)*User Mobility*: We set up a network with a LTE basestation and a single WiFi AP. The setup consists of 8 user flows such that 6 users are within the coverage of the WiFi AP. All users stream YouTube videos of average bit-rate 1.5Mbps. Initially, all the 6 users are placed close to the WiFi AP such that they receive good throughput and hence a smooth video. At about 30 seconds, 2 users are moved away from the WiFi AP at walking speeds such that they are still in the coverage of the WiFi AP. We plot the throughput obtained by 3 (Users#1,2 and 3) out of the 6 users over WiFi in Figure 11(b). Clearly, as the users move away from the WiFI AP, more resources are needed to meet the throughput requirement of the users causing network congestion. The throughput obtained by the WiFi users is insufficient causing stalls in their video streams. However the 2 LTE users, specifically Users#7 and 8 get sufficient throughput as shown in Figure 11(d) to stream the video smoothly as the LTE basestation has sufficient resources available. On the other hand, ATOM ensures that Users#1 and 4 are moved to the LTE basestation relieving the congestion in the WiFi AP. As seen from Figure 11(a), Users#2 and 3 receive throughput above their requirement of 1.5Mpbs sustaining good video quality. Although User#1 is moved to the LTE basestation at around 40 seconds into the experiment as shown in Figure 11(c), the LTE basestation has sufficient capacity to support the video rates of Users#1, 7 and 8. Hence, ATOM is adaptive to link quality fluctuations due to user mobility.

(ii)*User Flows Arrival/Departure*: In this experiment, we



(a) ATOM(AP) (b) ATOM (LTE BS) (c) NO-ATOM(AP) (d) Fine-grained traffic management

Figure 10: Efficacy of ATOM with network dynamics.

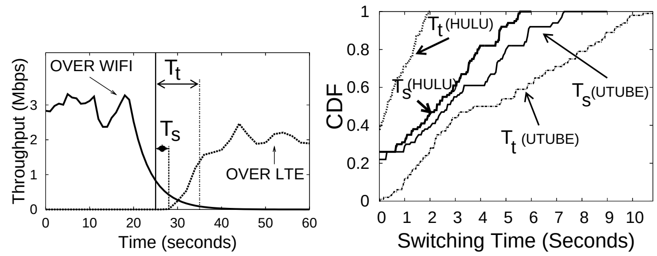


(a) ATOM (AP) (b) NO-ATOM (AP)

(c) ATOM (LTE BS) (b) NO-ATOM (LTE BS)

Figure 11: Efficacy of ATOM with user mobility.

setup a network with a LTE basestation and a WiFi AP. The setup consists of 4 users streaming YouTube videos of average bit-rate of 1.5Mbps. Users#1,2 and 3 are within the coverage of the WiFi AP while User#4 can only access the LTE basestation. To show the efficacy of ATOM with dynamic arrival or departure of flows, we introduce 2 WiFi users with background traffic at around 30 seconds into the experiment such that the flows are active for about 40 seconds. Figure 10(c) plots the throughput achieved by the 3 WiFi users for the case with NO-ATOM. Initially, the users receive throughput above their requirement of 1.5Mpbs. However, during the time period from 30 to 70 seconds, the throughput of all the 3 users falls below 1.5Mbps due to the presence of the 2 background flows on the WiFi AP during this time period. On the other hand, ATOM moves the video flow of User#1 to LTE basestation at around 30 seconds as shown in Figure 10(a),(b). ATOM is aware that the LTE basestation has sufficient capacity to support the video flow of User#1 without affecting the video of User#4. The throughput achieved by Users#1 and 4 on the LTE basestation is shown in Figure 10(b); traffic from the video flow of User#1 starts around 30 seconds on the LTE basestation. At around 70 seconds, ATOM moves the video flow of User#1 back to the WiFi AP since the 2 background flows ended during that time releasing resources of the WiFi AP. After 70 seconds, the video flows of Users#1,2 and 3 receive throughput above 1.5Mbps as clear from Figure 10(a) resulting in a smooth streaming for all the 3 users. Hence, ATOM is effective in improving user QoE and network utilization dynamically as user flows arrive and leave.



(a) Throughput (YouTube) (b) Switching Time

Figure 12: Benchmarking the ISS.

3) Fine-grained Adaptation: In this experiment, we show the ability of ATOM to perform fine-grained traffic management. The experiment is setup with 8 LTE users within the coverage of the WiFi AP and 4 LTE users outside the WiFi coverage. All the 8 users download a large file from the WiFi AP. One of the WiFi users (User#5) also streams a YouTube video of average rate 2Mbps. All the 4 LTE users stream the same YouTube video from the LTE basestation. Figure 10(d) plots the average number of stalls in the video session of the 4 LTE users and User#5. Scenario 1 represents the case where all the traffic of User#5 is mapped to the WiFi AP since the user is within the coverage of the AP. Clearly, the video flow of User#5 suffers significantly as the WiFi AP is congested. Scenario 2 represents the case with user-level traffic management where both the flows of User#5 (video and file-download) are moved to the LTE network. This results in the LTE network getting congested and the video of all the 5 users suffer. With ATOM's flow-level interface management, the video flow of User#5 is moved to LTE while the file-download flow is kept on WiFi. Since ATOM operates at the granularity of user flows, the increased flexibility allows ATOM to ensure good QoE by reducing the average stalls per user from 6-8 with NO-ATOM to 1-2 with ATOM.

4) Benchmarking the ISS: In this experiment, we investigate the switching time taken by the ISS specifically for HTTP-based video streaming since video traffic accounts for significant percentage of the total traffic. We measure the switching time using two metrics defined as: (i) Start Time (T_s): It is the time taken for downlink traffic to start on the new interface. (ii) Termination Time (T_t): It is the time taken for traffic to completely stop on the current interface. Both the metrics are measured relative to the time that the command to switch the interface is received by the client. Figure 12(a) shows how we measure T_s and T_t by plotting the throughput of a video flow that is moved from

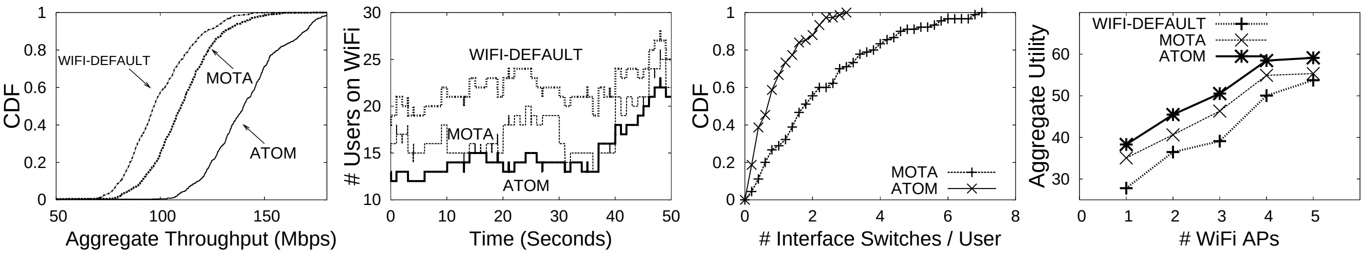
WiFi AP to LTE basestation at around 25 seconds. T_s is the time taken for traffic of the flow to start over LTE and T_t is the time taken for traffic to completely stop over WiFi. We setup the experiment by streaming a single video over WiFi initially and configure the ISS to switch the interface of the flow every 30 seconds between WiFi and LTE. We repeat the experiment for several different videos from YouTube (represents HTTP-PD) and Hulu (represents adaptive video streaming). Figure 12(b) plots the CDF of the two metrics T_s and T_t for the different video streams. Clearly, the median switching times are within a couple of seconds and hence, within the expected time-scale for the execution of ATOM. Notice that the times are larger for HTTP-PD streams (YouTube) than the adaptive video streams (Hulu). On further investigation, we noticed that players supporting adaptive video streaming typically request video chunks of lower size (typically 2-4 secs of video) than those requested by regular video streams like YouTube. Also, adaptive video players request the chunks at a rate that closely matches the playout rate to ensure adaptiveness to changing network conditions. This behavior results in Hulu streams having a lower T_s and T_t than those shown by YouTube streams. Given the growing popularity of adaptive video streaming, we expect most video services to show results similar to those shown with Hulu (We did see similar results with CBS, Netflix). Moreover, note that although YouTube streams have a relatively higher value of T_t, as seen in Figure 12(a), the amount of traffic downloaded during that time (25 to 35 seconds) is significantly less than the average rate of the video (2 Mbps) since the traffic consists of the residual bytes for video chunks that were requested before receiving the interface switching command and all subsequent chunks are requested from the new interface.

7.2 Simulations

Set-up: Although our prototype evaluation shows the efficacy and feasibility of ATOM in a realistic setting, we now study the efficacy of ATOM with a large number of active user flows. Large-scale experiments could not be performed on the prototype due to the unavailability of a large number of mobile users. We developed an in-house simulator on MATLAB® that can simulate a network of a single LTE basestation and multiple WiFi APs. We leverage path-loss models from 3GPP to generate the SNR (signal to noise ratio) at each user for the communication link from the LTE basestation as well as from the associated WiFi AP. We employ different rate tables for LTE and WiFi to choose the best link-layer rate for a user based on its current SNR. We randomly distribute the APs within the LTE cell. Also, we distribute the users in a uniform random fashion within the cell coverage such that there is a non-zero probability of a user not falling in the coverage area of any WiFi APs. The inter-access times of flows at each user are drawn from an exponential distribution and each user flow is active for a deterministic duration of 120 seconds. When active, each user flow has backlogged traffic in the downlink. The SNR at the users vary across different flows over time. The number of users and the parameter of the exponential distribution are jointly chosen such that the number of active user flows in the system varies from 20 to 40 in steady state. The MAC scheduler that performs fine-grained resource management, executes every 10 milliseconds and employs a PF-based scheduling policy for the LTE basestation and a RR-based scheduling policy for the WiFi APs. ATOM is executed every second and it is assumed that interface switching occurs instantaneously. We repeat our experiments for different topologies by varying the location of the clients, the number of clients and APs and the placement of the APs.

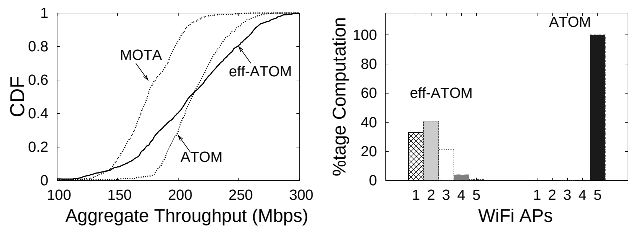
Reference schemes: We evaluate the performance of ATOM's NIA algorithm with the following techniques for interface selection: (i) WiFi-Default: This case represents the current deployments where the users always connect to an available WiFi AP. (ii) MOTA: MOTA [8] is a client-side solution that asynchronously executes the interface selection decision at the client to maximize the utility of a user. MOTA requires additional signalling about the load of each WiFi AP and LTE basestation to each client. Similar to ATOM, we employ a log utility function of the throughput for each user in MOTA. MOTA is executed every 1 second on each client and the LTE basestation and WiFi APs broadcast the required information every 10 seconds. Each client computes the expected throughput on every interface based on the update received from the APs and the basestation every 10 seconds. However, clients always have accurate information about the throughput on the current interface, i.e., the interface on which they have an active flow. Although MOTA may be hard to deploy as it requires additional signalling overhead (esp. WiFi APs that need to broadcast information about the link-layer rate of each user), it represents the ideal client-level solution for interface selection and hence, we compare it with the performance of ATOM.

1) Performance: We setup a network of a single LTE basestation with 3 WiFi APs in its coverage and vary the number of user flows. The aggregate throughput obtained by all the clients for the 3 scenarios is shown in Figure 13(a). Figure 13(b) depicts the aggregate number of user flows that are mapped to the WiFi APs over time for a small period in the simulation. As a centralized network-driven technique, ATOM is efficient in mapping the appropriate number of user flows to WiFi APs and LTE resulting in better resource utilization and load balancing than MOTA. Although MOTA does account for the load conditions of the basestation and the APs, it is not as efficient resulting in significantly lower throughput as compared to ATOM. In this particular case, ATOM is able to achieve an average aggregate throughput of almost 140Mbps with a 5 percentile throughput in excess of 100Mbps. On the other hand, WiFi-Default and MOTA achieve an average aggregate throughput of 90 and 110Mbps respectively, with a 5th percentile throughput of about 70 and 80Mbps respectively. A by-product of dynamic traffic



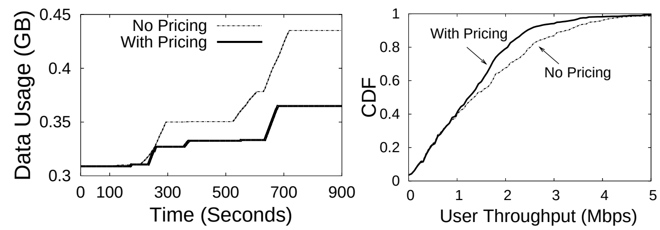
(a) Throughput (b) # Assigned WiFi Users (c) Avg Interface Switches (d) Aggr Utility

Figure 13: Large-scale evaluation of ATOM.



(a)Performance (b) Computation

Figure 14: Performance vs Computational efficiency.



(a) Data Usage over LTE (b) User Throughput

Figure 15: Considering interface cost

management is that it leads to interface switching for user flows. As seen in Figure 13(c), ATOM is effective in achieving a higher throughput while keeping the average number of switches per user per session below 0.5, while MOTA causes an average of 2 switches per user per session. Switching the interface of a user flow causes additional signalling in the mobile network and hence, excessive switching may be undesirable for an operator. To show the efficacy of improving fairness and QoE of user flows, we plot the aggregate utility obtained by all the 3 schemes. As seen in Figure 13(d), ATOM achieves better aggregate utility than MOTA for different topologies with increasing number of WiFi APs. ATOM thus achieves significant gains not only over naive schemes like WiFi-Default but is more efficient than distributed schemes like MOTA that rely on network load information.

2) Computational Efficiency: While ATOM is scalable, operating at the granularity of a single LTE cell, we also investigate an approach to trade-off performance of ATOM for reducing its computational requirements further. At each epoch, the modified algorithm, namely eff-ATOM is executed only for the WiFi APs that have a change in state and the assignment of the user flows of the other WiFi APs is kept unchanged. Change of state for a WiFi AP occurs if there was atleast a user flow that arrived or departed from the WiFi AP or there was a change in the average link layer rate of a user belonging to that WiFi AP in the previous epoch. We use a similar setup for this experiment as the previous one, with 5 WiFi APs. Figure 14(a) compares the performance of eff-ATOM with both ATOM and MOTA. Clearly, although there is a slight degradation in the aggregate throughput for eff-ATOM compared to ATOM, it still performs better than MOTA. Figure 14(b) depicts the percentage of cycles spent on computing the interface assignment for the number of WiFi APs. Specifically, eff-ATOM only computes the interface assignment for 1,2 and 3 WiFi APs 30, 40 and 20% of the times, while ATOM always computes the interface assignment for all the 5 WiFi APs. Hence in this case, if we consider the computation expense of a WiFi AP as a single unit, eff-ATOM is 65% more efficient than ATOM.

3) Pricing: To demonstrate the affect of incorporating pricing models (as discussed in section 4) within ATOM's framework, we conduct an experiment with a similar setup but add a cost to the LTE interface. The scenario mimics the case in today's networks, where the users have a data cap and pay for usage on the LTE network, while the usage on WiFi networks is free. We plot the CDF of the throughput obtained by one of the users in Figure 15(b) with and without incorporating pricing. With pricing, there is a deterrence for ATOM to move the user flow to the LTE network due to the associated cost. This results in a slightly lower throughput for the user. However, the data usage of the user over LTE is lower over time as shown in Figure 15(a) with the pricing function since the flows of the user are kept over WiFi more often than the case with no pricing. Hence, ATOM allows an operator to balance the utility for additional throughput (QoE) in an interface with its associated cost or data usage on a per user and/or flow basis.

8. RELATED WORK

Industrial Solutions: Several proprietary industrial solutions such as Qualcomm's CnE [27] and Interdigital's SAM [28] exist that aim to provide WiFi offloading techniques by providing intelligence mainly at the mobile devices. These solutions claim to provide user flow management framework across WiFi and 3G/LTE networks based on throughput and delay measurements. The rely on integration with the I-WLAN architecture in the network to provide seamless connectivity. Although not widely deployed, the existence of such solutions indicates the importance of the problem of WiFi offloading. Since these technologies incorporate context in their solution and provide management across 3rd party WiFi networks that are not managed by the operator, they can be used as complementary solutions to ATOM.

Client-side Optimizations: Several recent works [7, 8, 9, 10] have focused on designing fully distributed algorithms for network selection. Most of these solutions require assistance from the network regarding current loading information that adds overhead on the wireless link. As shown in our evaluations by comparing ATOM with one such technique namely MOTA, even with network load information, such solutions are not as efficient as a network-level solution. Another work Wiffler [29] provided measurement based evidence on the feasibility of using public WiFi for offloading 3G traffic. However, the scope of the work is limited to delay tolerant traffic and may require changes to the applications to support the framework.

Network Solutions: There is a plethora of work on network-driven algorithms for network selection or user association to ensure optimal load balancing across heterogeneous networks. A few of these works [6, 30, 31, 32] include a utility-based optimization framework with the objective of maximizing the throughput obtained by the users. However, these works (i) assume idealized settings with little or no consideration of practical constraints (ii) are tightly integrated with the basestation schedulers hindering their deployability and (iii) do not provide a end-to-end solution that ensures dynamic interface selection adaptive to changes in the mobile network. ATOM on the other hand is a comprehensive solution for traffic management of heterogeneous WiFi and LTE networks that is adaptive, light-weight and scalable that ensures deployability in today's mobile networks.

9. DISCUSSIONS AND CONCLUSION

While ATOM works well for static and mobile clients at moderate speeds, clients with vehicular mobility may require additional device support to use context information (e.g., speed) to ensure that such users are always treated as pure LTE users to avoid unnecessary switching given the limited coverage of WiFi APs. Under certain periods of high-dynamicity, ATOM may cause frequent interface switching for certain user flows. The design of ATOM can be easily extended to incorporate a deterrence for excessive switching for a particular user flow based on the history of switches for that flow. Although ATOM's current design is limited to work for HTTP flows, it can be easily extended to work for all types of flows with the use of TCP level proxies for non-HTTP flows (e.g., SOCKS proxies).

To summarize, we designed and implemented ATOM an end to end framework that enables an operator to effectively manage traffic flows across a heterogeneous network of LTE and WiFi APs. ATOM consists of two novel components: (i) NIA that dynamically assigns interfaces to user flows. By operating at the level of each LTE cell , NIA is both light-weight and scalable making it readily deployable (ii) ISS that provides seamless interface switching for HTTP-based flows to enable dynamic traffic management. ISS saves significant backhaul costs for the operator for HTTP-based video streaming and web browsing flows making it an attractive solution for current networks. Using both a LTE-prototype implementation and large-scale simulations, we demonstrate the efficacy of ATOM.

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