# LEVERAGING WIRELESS NETWORK VIRTUALIZATION FOR FLEXIBLE SHARING OF WLANs

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**and approved by**

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# ABSTRACT OF THE THESIS

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Providing air-time guarantees across a group of clients forms a fundamental building block in sharing an access point (AP) across different virtual network service providers. Though this problem has a relatively simple solution for downlink group scheduling through traffic engineering at the AP, solving this problem for uplink (UL) traffic presents a challenge for fair sharing of wireless hotspots. Among other issues, the mechanism for uplink traffic control has to scale across a large user base, and provide flexible operation irrespective of the client channel conditions and network traffic loads. In this thesis the **SplitAP** architecture is proposed that addresses the problem of sharing uplink airtime across groups of users by extending the idea of network virtualization. The architecture discussed in this thesis allows different algorithms to be deployed on it for enforcing UL airtime fairness across different client groups.

In this thesis, the design features of the **SplitAP** architecture are highlighted followed by results from evaluation on a prototype deployed with the two algorithms for controlling UL group fairness like: (1) Linear Proportional Feedback Control (LPFC) and (2) Linear Proportional Feedback Control plus (LPFC+). Performance comparisons on the ORBIT testbed show that the proposed algorithms are capable of providing group air-time fairness across wireless clients irrespective of the network volume, and traffic type. The algorithms show up to 40% improvement with a modified Jain fairness index.

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# DEDICATION

**To My Grand Parents and Parents**

# ABBREVIATIONS

| | |
|---|---|
| AP | Access Point |
| VAP | Virtual Access Point |
| WLAN | Wireless Infrastructure Local Area Network |
| ISP | Internet service provider |
| UL | Uplink |
| DL | Downlink |
| MADWIFI | Multiband Atheros Driver for Wifi |
| CSMA | Carrier sense multiple access |
| LPFC | Linear Proportional Feedback Control |
| LPFC+ | Linear Proportional Feedback Control plus (advanced) |
| FTP | File Transfer Protocol |
| MB | Mega Byte |
| IP | Internet Protocol |
| MAC | Medium Access Control |
| Mbps | Mega bits per second |
| TCP | Transmission Control Protocol |
| UDP | User Datagram Protocol |
| ORBIT | Open Access Research Testbed for Next-Generation Wireless Networks |

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# CHAPTER 1

# INTRODUCTION AND RELATED WORK

## 1.1 Introduction

The onset of ubiquitous wireless systems in the form of inexpensive handheld devices is expected to lead to an ever increasing deployment of wireless hotspots [12]. Differentiation in the quality of service provided on shared hardware for wireless Internet Service Providers (ISPs) provides a substantial challenge with more and more ISPs aiming to provide services at public locations such as airports, cafes and shopping areas. A mechanism is required to ensure that this access point (AP) sharing will work across a wide range of client hardware, while providing each user group (clients belonging to a single ISP) with aggregate air-time commensurate to the revenue contract of the ISP with the wireless equipment provider. Apart from providing baseline fairness in terms of air-time across different user groups, other requirements for sharing WLAN access point hardware across different ISPs include:

(1) Different broadcast domains,

(2) Different levels of security,

(3) Support different protocols above a basic L2 connection,

(4) Ease of deployment, and

(5) Minimum bandwidth loss for resource partitioning.

To solve this problem the **SplitAP** architecture is proposed in this thesis that employs wireless network virtualization. Network virtualization is a concept derived from the server systems area of research which has recently been applied to network sharing. Virtualization is a mechanism that allows for seamless sharing of a particular resource by using three key features: **Abstraction, Programmability** and **Isolation**. Each of these features is applied as shown in the Figure 1.


**Figure 1: A single wireless access point emulating multiple virtual access points. Clients from different networks associate with corresponding VAPs though they use the same underlying hardware.**

**Abstraction** allows the users of the system to use the **SplitAP** architecture with minimal changes to the client hardware or software. As shown in the Figure 1, virtual access points (VAPs) [4] are used that are supported by most commodity AP hardware to emulate the functionality of two different physical APs (ISP1, ISP2) with a single physical AP, thus allowing the use of the client MAC protocols and hardware without making any changes to them respectively.

In the setup, **programmability** is provided by allowing the person deploying the hardware to allocate different UL air-time quotas for individual virtual access points. Finally, **isolation** across groups of wireless users is provided through air-time control at the clients based on the information provided by the **SplitAP** controller running at the AP.

Since downlink air-time fairness has been studied previously [6], and a spate of recent applications such as those supported by web 2.0 [3], peer-to-peer file sharing [18], and video conferencing have resulted in significantly increased uplink air-time usage, the problem of uplink air-time control across the virtual networks formed by wireless user groups is addressed in this thesis. Through the use of a **SplitAP** prototype discussed here, the performance of our sample algorithms for providing uplink air-time fairness across user groups is shown, while providing all of the features discussed above. Specifically the contributions of this thesis are:

1) Proposal, design and implementation of the SplitAP software architecture based on the extension of the virtual access point functionality for sharing a single physical AP across groups of users.
2) Design and evaluation of the *LPFC* and *LPFC*+ algorithms for group UL air-time

control using the **SplitAP** setup on commercial *off-the-shelf* hardware.

3) Extensive evaluation to show that the results obtained on the **SplitAP** infrastructure are as per the requirement while achieving the system performance with minimal overhead.

## 1.2 Related Work

Among AP based infrastructures, DenseAP architecture proposed in [16], describes a mechanism for sharing airtime by managing handoffs across APs. Another setup to share downlink air-time has been discussed for WiMAX radios in [6]. The SplitAP setup explained in this thesis specifically deals with the problem of providing architecture for sharing UL air-time of a single AP across multiple WLAN user groups. In terms of the methodology itself, a comparison of wireless virtualization approaches is presented in [15]. However, it does not address the problem of fair sharing of UL air-time across client groups.

In the domain of air-time fairness, a body of work [14], [10], [7], [5] discusses the use of EDCA parameters such as contention windows and transmission opportunities for controlling airtime usage across clients. The study in [14] attempts to ensure fairness across competing uplink stations with TCP traffic using EDCA parameters. Time fair CSMA protocol proposed in [10] controls minimum contention window size to achieve estimated target uplink throughput for each competing station in multirate WLAN. In [5] authors suggest that in a proportional fair allocation based on 802.11e EDCA parameters, equal share of channel time is given to high and low bit rate stations and, as a result, high bit rate stations can obtain more throughput. Another study in [7] proposes two control mechanisms for airtime fairness, one using AIFS and the other using contention window size. The studies in [14], [10], [7], and [5] are based on simulations.

One study in [17] proposes a Time Based Regulator system that achieves uplink air-time fairness by ensuring equal "long term" channel occupancy time for every node in the WLAN. Though this study presents results based on an implementation, it does not deal with the problems of clients sending traffic with different frame sizes, offered loads, and sharing of airtime across user groups. The TWHTB system discussed in [8] uses information on current channel quality to the respective station associated with AP to schedule downlink transmission to that particular station by limiting frame transmission rate. However, this scheme does not take into account Uplink flows and corresponding traffic variations. Another study discussed in [11] discusses an approach where each station monitors the number of active stations and calculates the target access time based on this information. The study uses sniffing on the client side, while also requiring modification of NAV field in the MAC header, and results are based on simulations.

In addition none of these studies address the problem of enforcing client-group UL airtime fairness which is addressed by algorithms run on our SplitAP setup.

Rest of the thesis is organized as follows. Chapter 2 gives a brief overview of what network virtualization is and how can it be leveraged to solve the problem we are tackling in this thesis. Chapter 3 discusses the problem of providing uplink air-time fairness across user groups, and presents the design of our SplitAP architecture. Chapter 4 presents a discussion on the two sample algorithms evaluated with the SplitAP framework. Chapter 5 presents the results from the system, and finally, chapter 6 discusses the conclusions and future work.

# CHAPTER 2

# NETWORK VIRTUALIZATION

This chapter begins by providing an overview of what virtualization is. This is followed by a discussion about how this concept is extended to both wired and wireless networks. This is followed by how the network virtualization is applied for the problem statement covered in this thesis using the Virtual Access Points (VAPs) feature provided by MADWIFI driver for atheros chipset to create multiple virtual APs (slices) from one physical access point. Finally, we conclude this chapter with some basic experiments to test the performance of VAP.

## 2.1 WHAT IS VIRTUALIZATION?

Virtualization is a framework or methodology of dividing the resources of a computer into multiple execution environments, by applying one or more concepts or technologies such as hardware and software partitioning, time-sharing, partial or complete machine simulation, emulation, quality of service, and many others [19].

The general process of virtualization is best explained with Figure 2.1. The hardware machine to be virtualized lies at the bottom of the virtualization solution. Virtualization may or may not be supported on this machine directly. On top of the actual hardware resource there is a hypervisor more commonly known as Virtual Machine Monitor (VMM). This layer acts as an abstraction between the hardware and the operating system (OS).

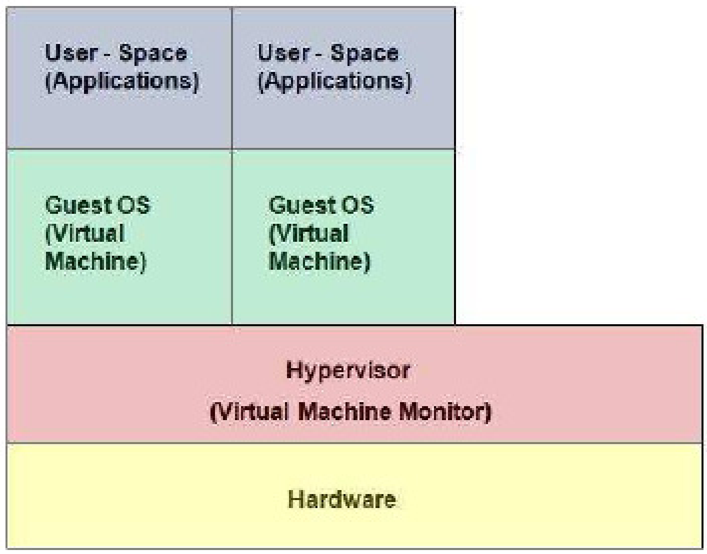



**Figure 2.1: Layered abstraction of virtualization [1]**

If the OS performs the functions of the hypervisor itself, then such operating system is called the host operating system. The actual virtual machines (VMs) form the topmost layer of the entire virtualization solution. These VMs are isolated operating systems, and they function as if the entire host hardware platform is dedicated to each one of them. These VMs are independent of each other and can have applications associated with them.

Having understood what virtualization is, we take a look at the different types of virtualization techniques that are possible [1] -

### 2.1.1 Hardware emulation

In this technique, virtualization is provided by creating virtual machines that emulate the hardware itself. This technique allows OS to run without making any modifications to it. The main drawback of this technique is that it is very slow.

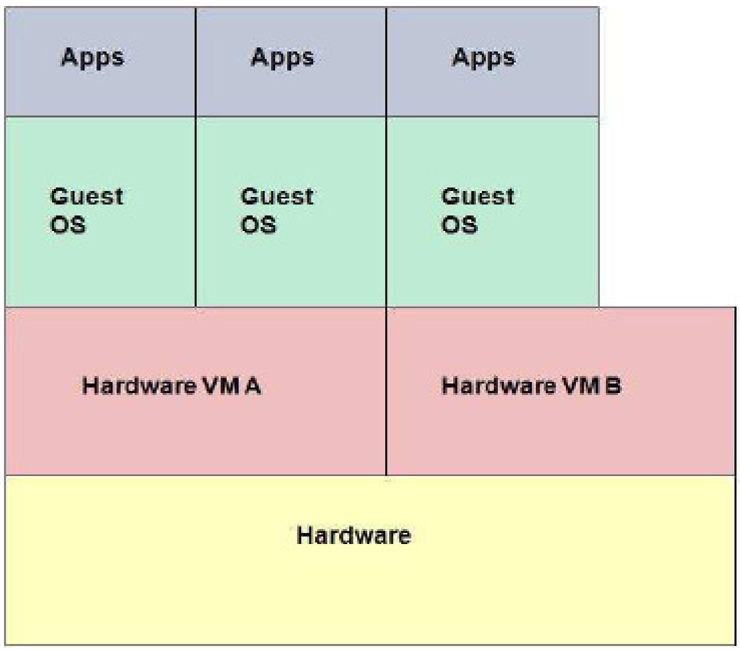



**Figure 2.1.1: Hardware emulation [1]**

Example of hardware emulation is QEMU. Figure 2.1.1 shows the basic architecture of Hardware Emulation.

### 2.1.2 Full virtualization

Virtual machine manager is used to mediate between the host machine and guest OS in this type of virtualization technique.

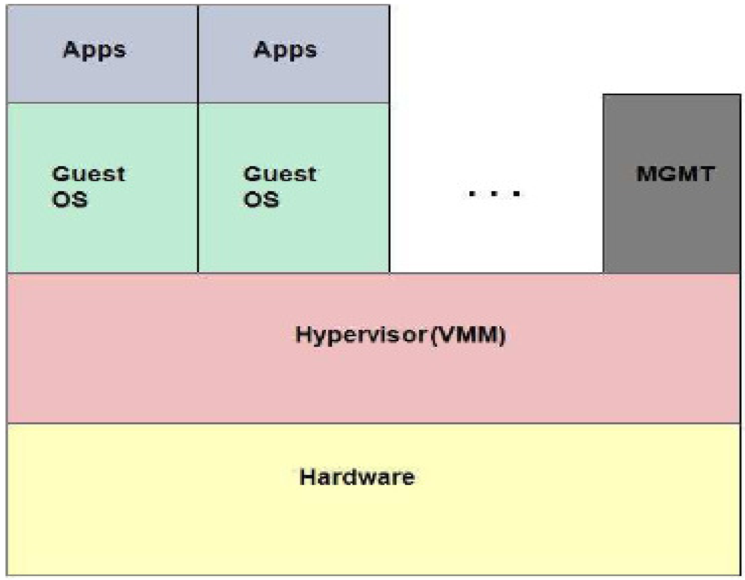



**Figure 2.1.2: Full virtualization [1]**

This requires some protected instructions to be trapped and managed by the VMM since the underlying hardware is shared by all the virtual machines (VMs). This technique also allows the OS to run unmodified. At the same time it does need to be compatible with the underlying hardware. VMware and z/VM are the examples of this type of virtualization. This technique is as depicted in Figure 2.1.2.

### 2.1.3 Paravirtualization

This method is similar to full virtualization; wherein it uses a hypervisor to mediate access to the hardware; but it requires that the guest operating system has some virtualization-aware code present in it. Figure 2.1.3 explains this technique. This mechanism does away with the need to trap any privileged instructions, since the guest OS is aware of the virtualization process. Paravirtualization comes closest to offering performance that is close to that of an unvirtualized system. Xen and UML make use of the paravirtualization technique.

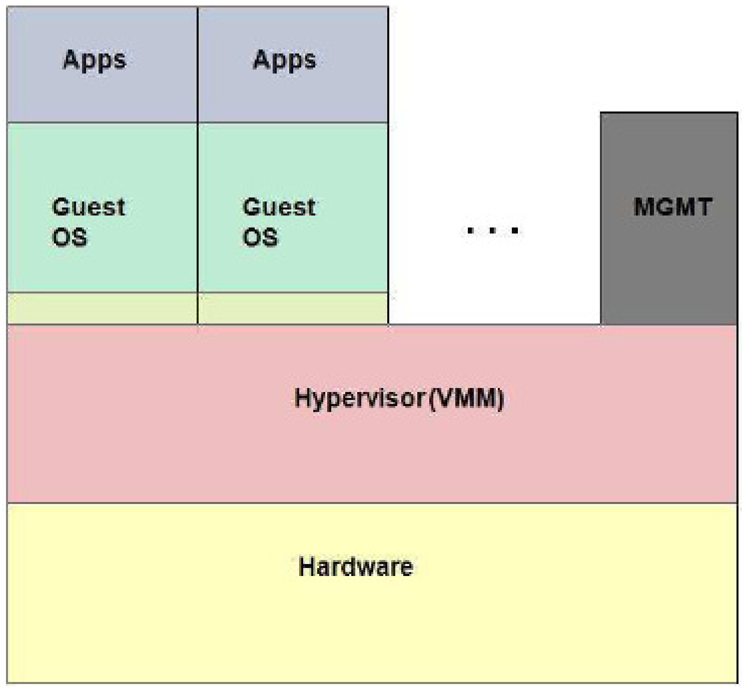



**Figure 2.1.3: Paravirtualization [1]**

## 2.1.4. Operating system-level virtualization

The final technique as shown in Figure 2.1.4 virtualizes server on the top of the operating system itself. This method isolates the independent servers from each other, while supporting the same operating system to be used by them. This can provide native performance at the cost of changes to the operating system kernel. OpenVz is an example of operating system-level virtualization technique.

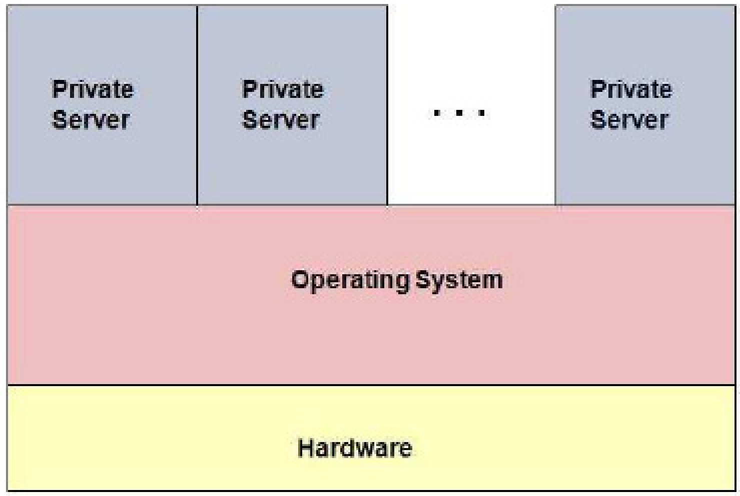



**Figure 2.1.4: Operating system-level virtualization block diagram [1]**

## 2.2 Leveraging virtualization for networks

Network virtualization provides a powerful way to run multiple networks, each customized to a specific purpose, at the same time over a shared substrate [21]. Network virtualization is intended to optimize network speed, reliability, flexibility, scalability, and security. It delivers increased application performance by dynamically maximizing network asset utilization while reducing operational requirements [22]. It is said to be especially effective in networks that experience sudden, large, and unforeseen surges in usage [23].

## 2.3 Wireless Access Point Virtualization

This section talks about how the virtualization concepts and techniques explained in previous section are applied for virtualizing a wireless access point.

### 2.3.1 Why is virtualization needed?

Virtualization enables a single machine/node to emulate multiple logical instances of a required physical/hardware resource within the same or different slices. One of the main challenges with the radio nodes on ORBIT grid is to provide a setup where multiple experimenters could run experiments which involve a wireless access point and their respective stations/clients as a part of their experimentation setup. This configuration is achieved by using virtual access point (VAP) functionality provided by 802.11 driver that is further explained in the next section.

### 2.3.2 Virtual Access Points (VAPs)

A VAP is defined as a logical abstraction that could be run on a physical access point which then emulates the behavior of a conventional access point to all the client stations in the WLAN [24]. Using a VAP allows for two or more AP mechanisms to share the same channel thereby helping channel and energy conservation. In contrast to the TDMA approach for channel multiplexing, VAPs are more suitable for running short and long-term experiments with less stringent constraints on the current testbed resources. The concept of VAPs is incorporated in the 802.11 driver, which operates just above the MAC layer and below the IP layer. The driver provides the multiple AP abstraction to the higher layers though it is operating on a single lower layer. Hence all the protocols operating on the machine are agnostic to the presence of the abstraction.

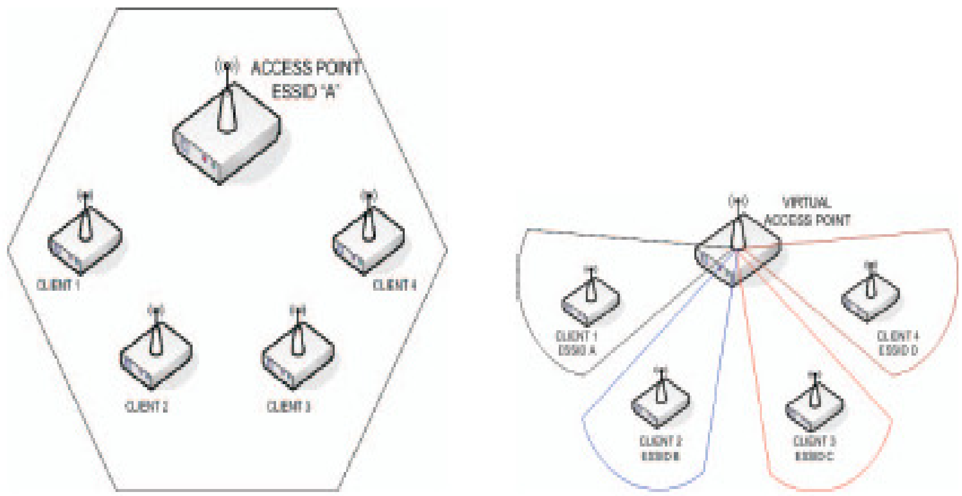
Compared to the TDMA approach, the VAP does not require tight synchronization among the different experiment nodes. However, this scheme requires traffic shaping and is limited to fixed star topology wireless networks [15]. Since channel conservation is of prime importance, we choose to use VAP methodology on the ORBIT grid for evaluation of air-time fairness provided by SplitAP mechanism.

### 2.3.3 Baseline Throughput Performance with VAP

Throughput, latency and jitter are usually the three main parameters, which determine a user's utilization and experience on a network device. Throughput for individual experiments in a virtualized environment is expected to be lesser than those under single user conditions. However, performance under these conditions is largely contingent on how fairly the resources are shared. A virtualized channel is shared among multiple users running simultaneous experiments and the end performance can largely be a function of individual experiment parameters rather than just a fair share between users. This study was insightful in determining that a VAP provides significant advantages over a conventional physical access point setup [15].

#### VAP Overhead

A VAP creates an abstraction of multiple physical access points running from the same hardware for the stations associating with it. Creation of these logical entities requires state maintenance and independent management signaling for each of the networks managed by each VAP. The overheads of maintaining the state of multiple networks at a single hardware device is studied in [15]. The experimental setup is as shown in Figure 2.3.3(a) and Figure 2.3.3(b).




(a) A physical access point and four clients

(b) Four virtual access points and their individual clients

**Figure 2.3.3: Experimental setup for performance evaluation with physical and virtual access points [15]**

Figure 2.3.3(a) shows a setup with one AP and all four clients within the same network. Figure 2.3.3(b) has the same nodes. However, each client belonged to a different logical network created by the VAPs. Care was taken to ensure that there is no capture within the network by choosing client nodes such that they had comparable RSSI at the access point. Results were evaluated for both uplink and downlink performance with a saturated channel and equal offered load per client. Other experiment parameters were maintained as shown in Figure 2.3.3(c). Figure 2.3.3(d) plots the observed per client throughput $(\frac{Mbits/sec}{client})$ for uplink and downlink traffic.

| *Parameter* | *Value* |
|---|---|
| *Channel Rate* | 36Mb/sec |
| *Aggregate Offered Load* | 50Mb/sec |
| *Experiment Duration* | 5 Minutes |
| *Averaging Duration* | Per Second |
| *Operation Mode* | 802.11a |
| *Traffic type* | Uplink |
| *Chipset* | ATHEROS |
| *Driver* | Madwifi(0.9.3.1) |

**Figure 2.3.3(c): Experimental parameters used with ORBIT nodes [15]**

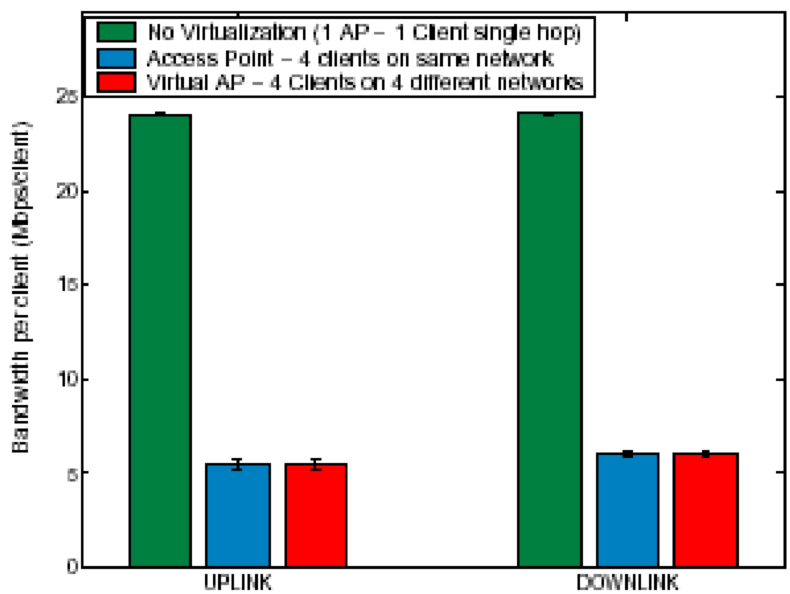



**Figure 2.3.3(d): Impact of virtualizing using channel multiplexing approaches. [15]**

Performance of a single client with a single access point was taken as a reference for comparison. Key observations that were made from the results are:

• As with any time sharing approach, the entire bandwidth (which is seen in the scenario with 1 client) was shared across 4 clients.

• There was a slight deterioration in uplink traffic performance with both the AP and the VAP as compared to the reference flow with 1 client.

• There was no added deterioration with uplink traffic using VAPs for having clients on multiple networks, as compared to an AP with all clients in one network. Hence, it was concluded that the deterioration was seen in both cases, which lead to a net channel throughput decrease of 9.75%. This decrease for the virtualized scenario as compared to no vitualization was due to the increased channel contention overhead.

• Downlink overheads for both AP and VAP with 4 clients were negligible as compared to that with a single client.

• Error bars for both cases show little variance in throughput. Hence it was concluded that using a VAP adds no conspicuous overhead to the throughput performance of an AP.

This behavior was confirmed by investigating the source code for the MADWIFI driver where the VAPs are created. The driver does minimal additional processing to differentiate between the packets received for the different virtual interfaces. The above study suggests that experiments evaluating aggregate throughput with test setups running a single AP or multiple VAP should generate comparable results with the channel utilization being determined by the number of clients [15].

# CHAPTER 3

# SPLITAP DESIGN OVERVIEW

Throughout this thesis the notion of *slices* is used to refer to the resources allocated to a group of users belonging to a single ISP. The terms *groups* or *slices* will be used interchangeably henceforth. Our infrastructure enforces fairness in uplink (UL) airtime usage across slices, thus allowing individual ISPs to fairly share the underlying WLAN hardware and the corresponding channel. We start with a formal definition of the problem of sharing UL airtime across a group of users, followed by a conceptual description of our virtualization based design. Eventually, the details of the algorithms used for UL airtime allocation are discussed.

## 3.1 Group Uplink Airtime Fairness: Problem Statement

Consider a set of $M$ client groups (slices) with each group $S_i$ having $N_i$ clients. Let the fraction of UL air time allocated for every slice $S_i \in M$, be denoted by $W_i$. $W_i$ for each slice is decided during the time of deployment of the infrastructure and can be dependent on a wide range of criterion like pricing, importance of the group and so on. If $\phi^i_j$ denotes the measured UL air time consumed by the client $j \in S_i$ slice, the fraction of UL air-time used by every client associated with the access point is calculated as $C^i_j$:

$$C_j^i = \frac{\phi_j^i}{\sum_{p=1}^{M} \sum_{q=1}^{N_i} \phi_q^p} \quad (1)$$

The condition of group fairness requires that, the total measured UL airtime for all clients within a slice $S_i$ is limited to $W_i$:

$$\forall\{i \in M\}, \quad \sum_{j=1}^{N_i} C_j^i \leq W_i \quad (2)$$

The above condition should be fulfilled while placing no limitation on the individual values of $C_j^i$ i.e. all nodes within a single slice $S_i$ should be able to share the UL airtime fairly, independent of the usage on other slices. Hence, in the worst case every client should be able to utilize UL airtime $0 \leq C_j^i \leq W_i$ as long as the Equation (2) is not violated and all clients within $S_i$ share the available UL airtime fairly.

Qualitatively summarizing the constraints of the slice/group fairness mechanism:

(1) Flexibility: If the channel usage is below saturation, and there are no hard guarantees, each client should be able to access the entire available channel time for the slice,

(2) Within a group: Sharing of UL airtime should be fair and equal,

(3) Scalable: Should work with a large number of clients without significant control overheads,

(4) Adaptable: Should be able to comfortably adapt to changing environment with dynamic addition or removal of wireless clients, the network load, protocol type and the channel conditions for individual clients.

Hence, to allow deployment of algorithms that will be able to realize such a group airtime fairness mechanism, our SplitAP infrastructure will need to provide all needed control and measurement features while being transparent to the users of the system.

## 3.2 Virtualization Based Design

We will now discuss how each of the virtualization features is implemented as a part of our SplitAP architecture.

Abstraction: The functionality of virtual access points is employed and extended which is available as a standard feature on commercial access points for emulating multiple virtual access points on a single physical access point while operating on the same wireless channel [4]. Using this feature the physical AP will be able to broadcast beacons for independent virtual networks (ISPs). Hence clients belonging to different ISP slices can see the ESSID of their ISP and associate with it, thereby making client side connectivity transparent and simple.

Programmability: Each of the ISPs should have independent control of settings in their network. Using virtual access points, different features can be set per WLANs such as different security policies, broadcast domains, IP settings, independent control of MAC settings such as aggregation and *802.11e* based WMM parameters.

Isolation: Isolation across virtual networks (client groups) is a fundamental requirement for supporting multiple networks and will be the main topic discussed in this thesis. Ideally, this could be done through a strict TDMA scheduler across the virtual networks. However, such a scheduler would require a large change in the MAC mechanism of the clients, thus making them completely incompatible with other 802.11 based commercial access points. The SplitAP mechanism[1] proposed in this thesis is an incremental design to the existing *802.11* framework and is currently capable of existing as a stand alone entity outside of the driver. The functionality in our system is split as shown in the Figure 3.2.

The SplitAP controller at the AP is responsible for emulating the virtual access points, accounting of traffic by client groups, and determining the weights of UL airtime for each group. The client software is responsible for enforcing the commands broadcasted by the controller and reporting usage statistics like the physical layer rate and the average packet size reported by the client interface. The remaining discussion will focus on the implementation of individual components, followed by a brief overview of the algorithms for providing uplink airtime fairness across the ISP slices.

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[1] A brief overview of this work is also available in [25].

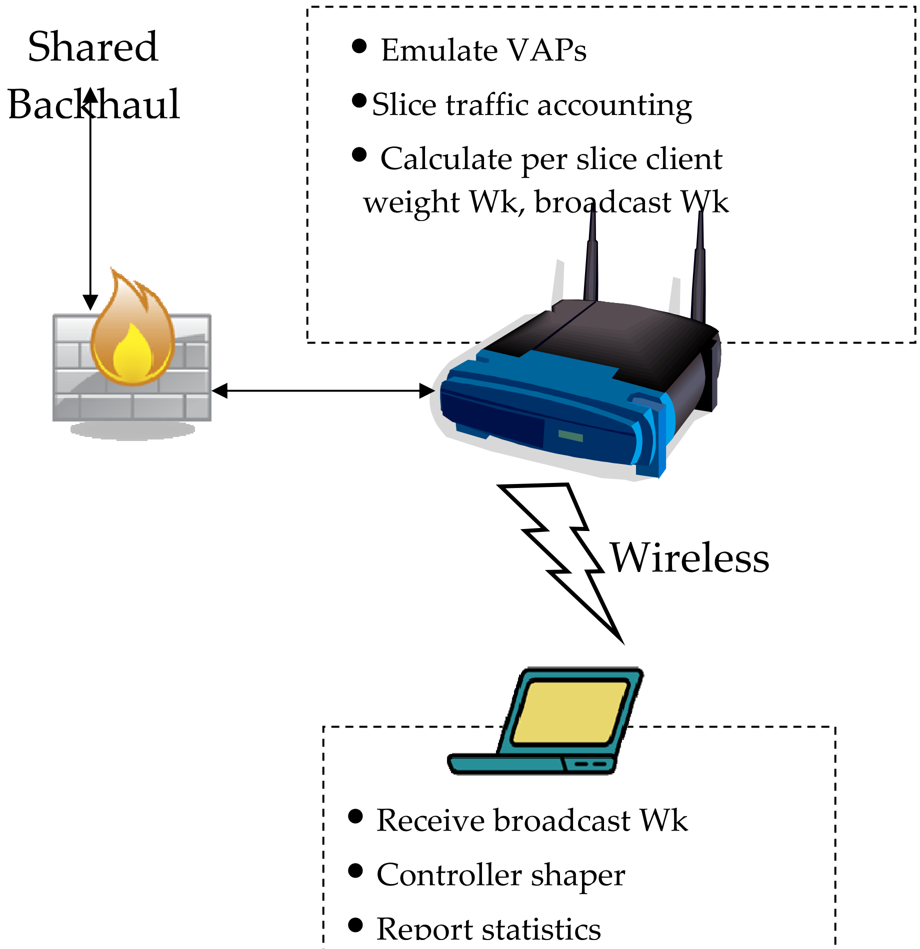


**Figure 3.2: A single wireless access point emulating multiple virtual access points. Clients from different networks associate with corresponding VAPs though they use the same underlying hardware**

## 3.3 SplitAP Controller

The access point infrastructure runs a multi-threaded ruby controller that performs the actions described in Algorithm (1). In the controller, *sliceID* is a unique identifier used for identifying independent slices owned by different ISPs. The algorithm computes slice UL airtime usage *time*[*sliceID*] for every *sliceID*, by iterating and determining the UL airtime usage reported by individual clients within every slice *sliceID*. Based on this estimate, it determines the offset of the actual slice utilization from the allocated UL airtime fraction. If this offset is greater than a threshold (Θ), the AP controller uses UDP broadcast as a means of sending $C_{sliceID}$ to clients to limit control traffic, since the number of control messages are now dependent on the number of slices rather than number of clients. Ideally, these $C_{sliceID}$ will be included in the beacons of individual virtual access points, thereby eliminating the need for a separate signaling mechanism. $C_{sliceID}$ the maximum UL airtime fraction that can be consumed by any individual client within the slice *sliceID*. The value of $C_{sliceID}$ is always chosen as inversely proportional to the UL airtime utilization for that slice. This fraction of channel time is calculated based on the previously broadcasted value and the corresponding slice utilization. *LPFC* and *LPFC*+ algorithms discussed later are two means of calculating $C_{sliceID}$ based on current UL airtime utilization numbers and or the number of associated clients.

**Algorithm 1:** The SplitAP controller running at the AP that monitors slice usage and correspondingly broadcasts slice weights to clients.

```
W_{0..M} = init_slice_weights()
while True do
    foreach sliceID = getNextSlice() do
        time[sliceID] = 0
        foreach clientID = getNextClient(sliceID) do
            rate = getPhyRate(clientID)
            bytes = getDataVol(clientID)
            cl_time = (bytes×8)/rate
            time[sliceID] + = cl_time
        end
        δ = time[sliceID] - W_sliceID
        if (abs(δ) > Θ) then
            C_sliceID = getWt(sliceID, slice_wt, δ)
            broadcast(sliceID, C_sliceID)
        end
    end
end
```

## 3.4 Client Plugin Design

In the current design, the client needs to install an application that allows the user to connect to a SplitAP based wireless service provider. Eventually, to make this application platform independent, it could be implemented as a web browser *plugin* that controls client's UL traffic based on commands from the controller. The client software stack in the current SplitAP architecture is as shown in Figure 3.3.

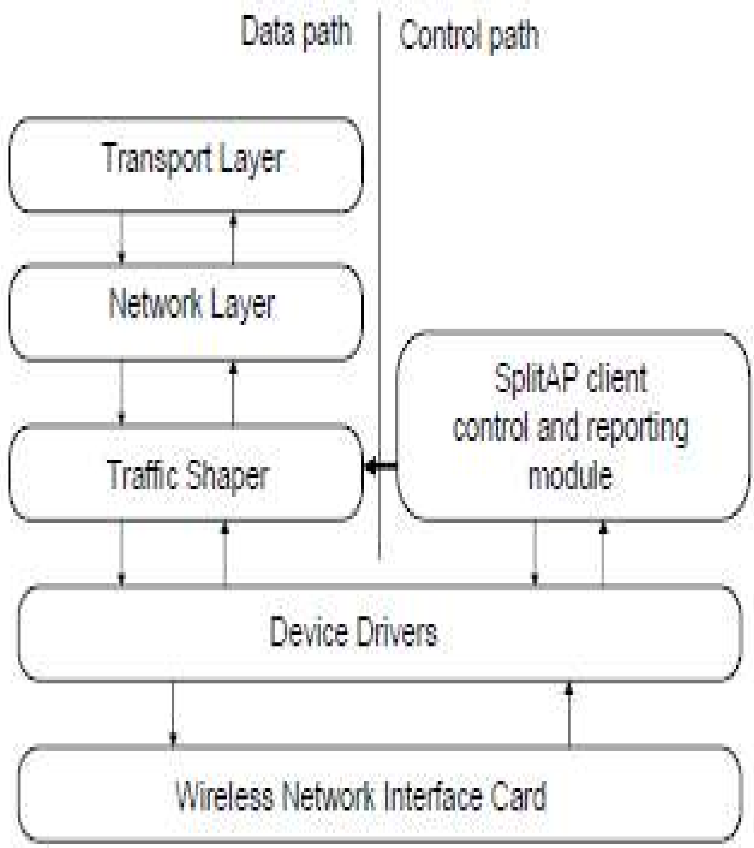


**Figure 3.4: Network stack at the wireless client associating with the SplitAP infrastructure**

The SplitAP client control and reporting module is responsible for two functionalities:

(1) Determining and reporting client side parameters such as physical layer rate (through access of the rate table), and average packet sizes by querying the *proc* filesystem or using the driver statistics.

(2) Converting the maximum airtime limit enforced by the SplitAP controller to a rate value, and accordingly controlling the shaping module to rate limit the client. The

shaping module is implemented by using the Click [13] modular router that transparently controls outbound traffic from the interface.

## 3.5 Algorithms for deployment with SplitAP

The SplitAP design offers a convenient way to deploy different algorithms on the AP for controlling uplink airtime across slices. Each of the algorithms discussed in this section are ways to implement the *getwt()* function discussed in Algorithm (1) and provide the value $C_{sliceID}$, which is the maximum airtime that can be consumed by any client in Slice $S_{sliceID}$.

### 3.5.1 Algorithm(1): LPFC

This is a simple linear proportional feedback control (LPFC) based algorithm that uses a dynamic estimate of the number of clients associated with the AP to calculate the $C_{sliceID}$. Information on the number of clients associated with the AP is available in the SplitAP controller through querying of the *proc* interface on the AP. The algorithm calculates $C_{sliceID}$ simply by determining current number of clients in the slice $S_{sliceID}$ and proportionally splitting the available (quota of) airtime $W_{sliceID}$ among the number of clients $N_{sliceID}$ within the slice. The SplitAP architecture allows this corrected $C_{sliceID}$ to be broadcasted every one second or at another interval desired by the ISP using the slice.

### 3.5.2 Algorithm(2): LPFC+

Instead of generating and broadcasting the $C_{sliceID}$ purely based on the slice UL airtime quota and number of clients in the slice, the LPFC+ algorithm relies on monitoring the current UL airtime utilization for the slice, which is available through the SplitAP client reports and appropriately controlling $C_{sliceID}$. The algorithm selects $C_{sliceID}$ in such a way that even if the offered load by clients in a slice is not the same, it allows the clients to increase traffic, by increasing $C_{sliceID}$ until the UL airtime quota for the slice is reached. If the quota is exceeded (or under-utilized), the LPFC+ controller proportionally reduces (or increases) $C_{sliceID}$, the maximum airtime that can be used by any client in the Slice *sliceID*. As with the LPFC algorithm, the $C_{sliceID}$ can be broadcasted every one second or at any other value desired by the ISP owning the slice.

# CHAPTER 4

# EXPERIMENTAL EVALUATION AND RESULTS

All experimental results presented in this evaluation are based on the clients with Atheros 5212 chipsets, and using Madwifi 0.9.4 [2] drivers. The clients are all operating in the 802.11a mode with a frame size of 1024bytes, and 54Mbps physical layer rate unless mentioned otherwise. Traffic is generated with the Iperf tool [1]. We begin with a brief definition of the metrics used, followed by baseline performance of the *LPFC* algorithm and a comparison with *LPFC*+.

## 4.1 Metrics

Preliminary evaluations with a small number of clients will be based purely on comparison of UL airtime allocated to individual slice. Further, in our evaluations, we modify and use the Jain fairness index [9] for determining weighted UL airtime fairness across flows and flow groups.

Modified Jain Index: Let the sum of fraction of channel time used by all clients in slice $k$ be denoted as $C_k$. Then,

$$I = \frac{\left(\sum_{k=1}^{N} C_k\right)^2}{N \times \sum_{k=1}^{N} C_k^2} \qquad (3)$$

The fairness index (*I*) determines the global variation in channel utilization across slices. We further scale the airtime by slice quotas to evaluate fairness under saturation with different slice weights, while also accounting for performance deterioration due to bad channel quality.

## 4.2 Baseline Performance With LPFC

To measure the baseline performance with the *LPFC* algorithm, we consider a setup with two clients on different slices sending UDP UL traffic using Iperf traffic generator.

**Varying Transmission Rates** In the first experiment, we vary transmission rates of the two clients on Slice 1 and 2 as shown on the x-axis in Figure 4.2(a), Figure 4.2(b) Figure 4.2 (c) and Figure 4.2(d). We observe that, in the vanilla case (without the SplitAP mechanism running the *LPFC* algorithm), the air-time used by the two clients are inversely dependent on the transmission rates. Also, the aggregate throughput achieved using SplitAP framework is slightly higher as against the traditional Vanilla system. This is a result of statistical multiplexing of packets by the CSMA MAC operating as a part of the 802.11 DCF mechanism.

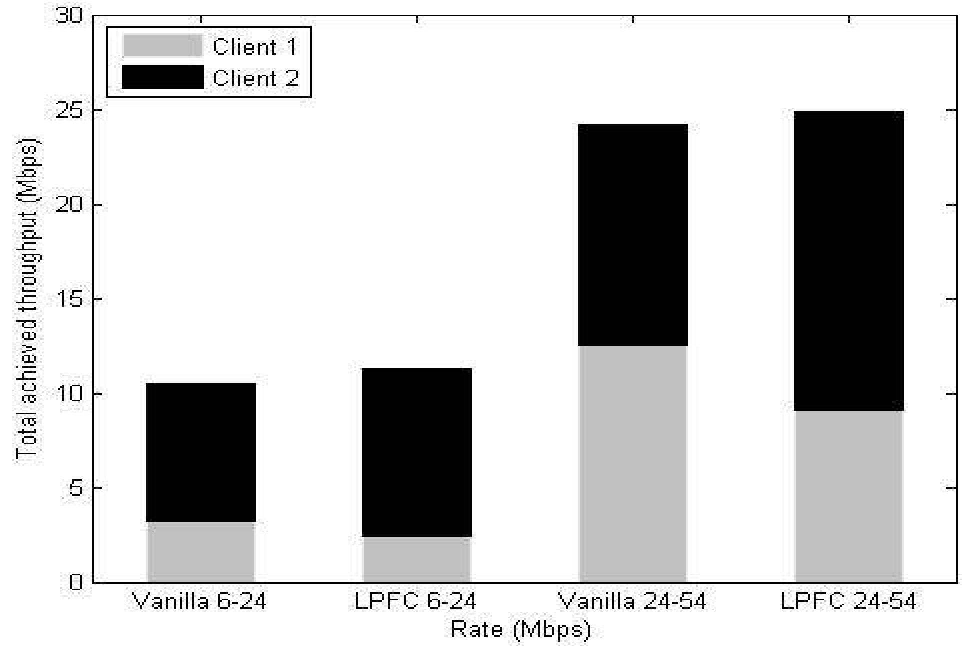


**Figure 4.2(a): Varying rate experiment (50 – 50 sharing) – Total Achieved Throughput**

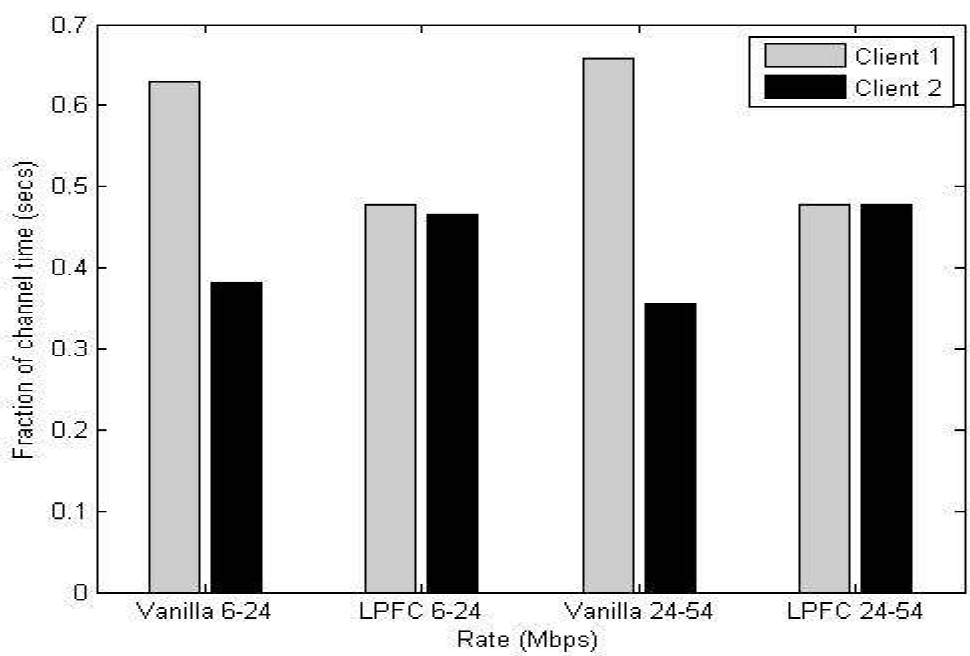


**Figure 4.2(b): Varying rate experiment (50 – 50 sharing) - Airtime Utilization**

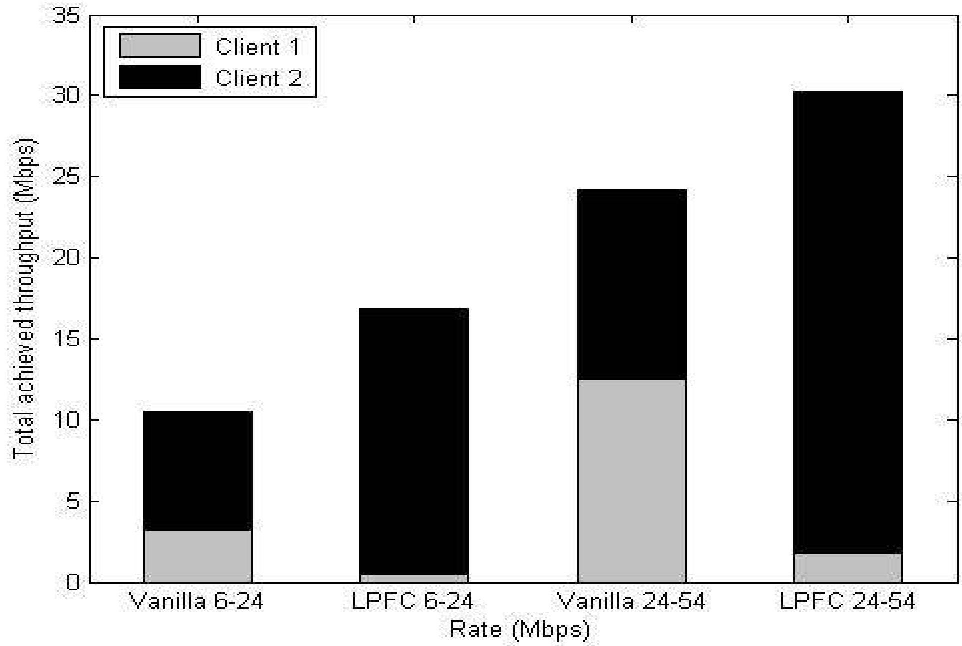


**Figure 4.2(c): Varying rate experiment (10 – 90 sharing) – Total Achieved Throughput**

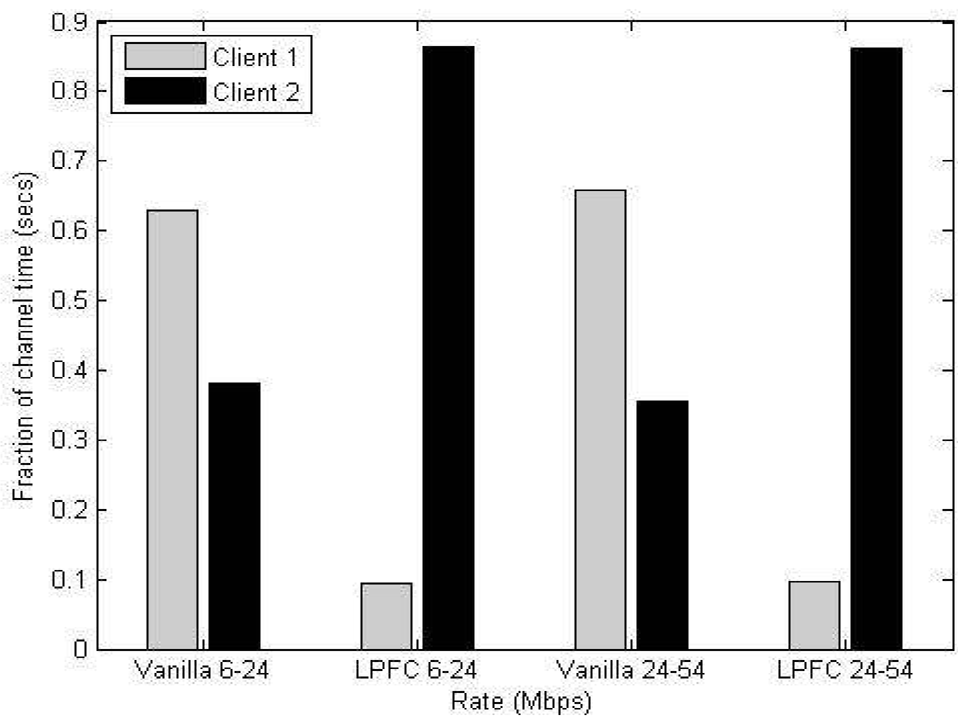


**Figure 4.2(d): Varying rate experiment (10 – 90 sharing) – Airtime Utilization**

**Varying Packet Sizes** Now we will vary the packet size of the uplink traffic from each client to check its impact on the overall sharing of air time at the access point for the two clients.

As seen in the results in Figure 4.2(f) and Figure 4.2(h), the airtime consumed at the access point without the use of our scheme (vanilla) is directly dependent on the size of the packets used by the uplink traffic. Typically, this results from a statistical multiplexing of packets over the air. However, using our SplitAP infrastructure with the *LPFC* algorithm we are able to control uplink traffic in direct proportion to the air time usage by each client. Our scheme accounts for the extra airtime spent in channel accesses and PHY/MAC overheads with smaller packet sizes resulting in fair sharing across the clients and thus virtual networks. This is also evident from the aggregate achieved throughput results as seen in Figure 4.2(e) and Figure 4.2(g). It is observed that the aggregate throughput achieved using SplitAP framework is comparable with the traditional Vanilla system. As before we observe that our infrastructure allows control of air-time across the clients in a preset 50 - 50 and 10 – 90 percentage. This percentage could be easily varied.

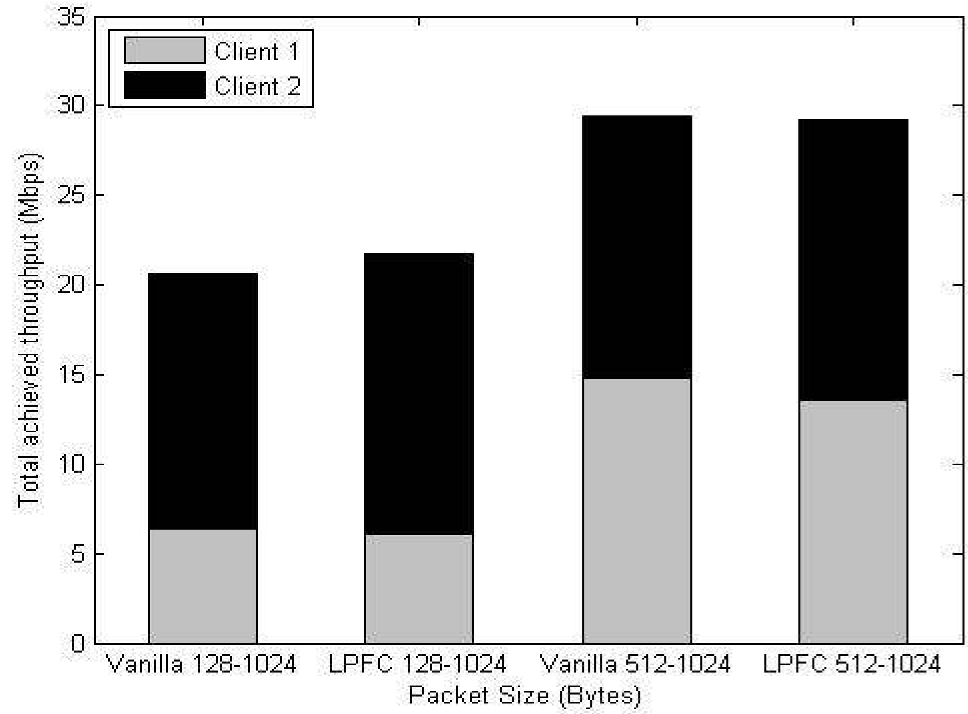


**Figure 4.2(e): Varying packet size experiment (50 -50 sharing) – Total Achieved Throughput**

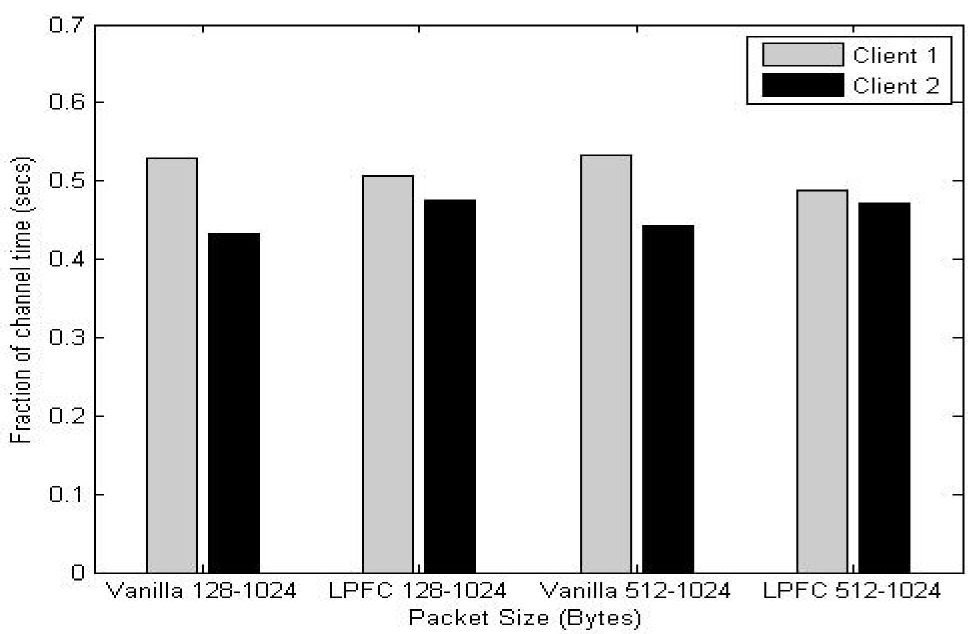


**Figure 4.2(f): Varying packet size experiment (50 -50 sharing) – Airtime Utilization**

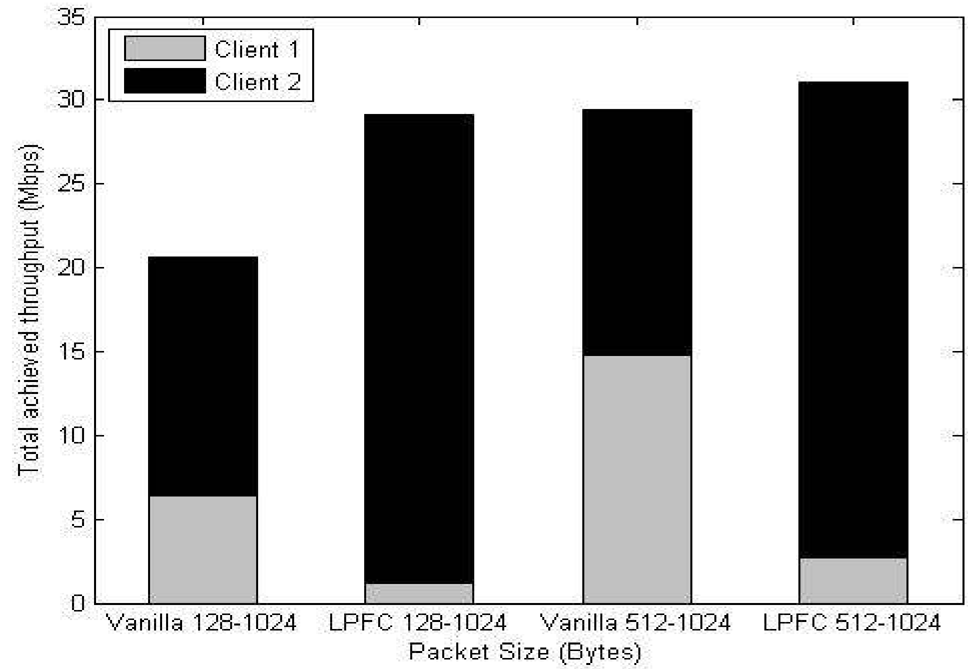


**Figure 4.2(g): Varying packet size experiment (10 - 90 sharing) – Total Achieved Throughput**

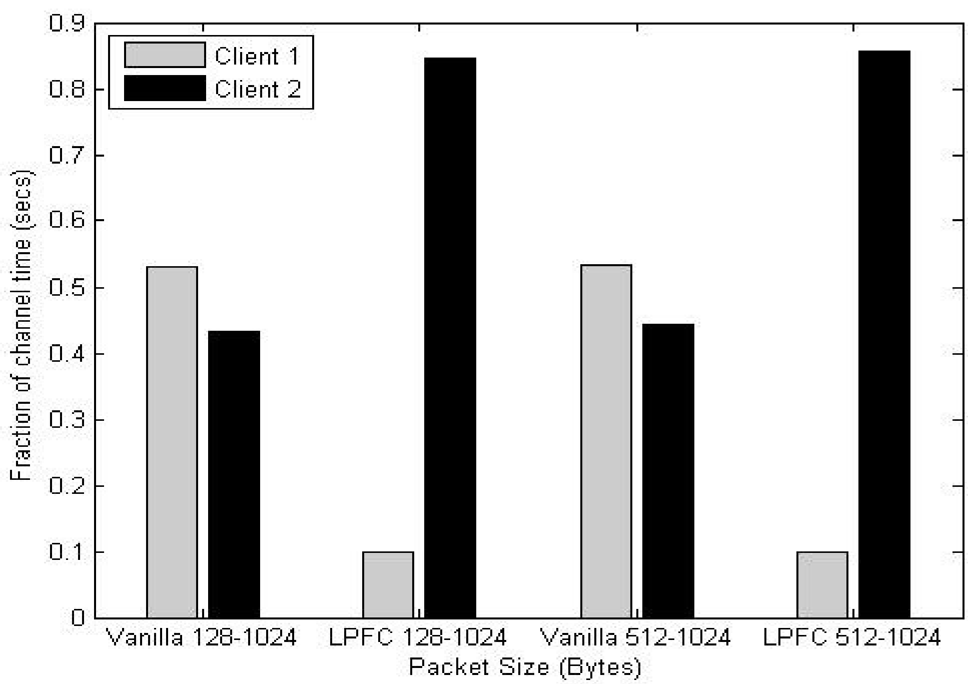


**Figure 4.2(h): Varying packet size experiment (10 - 90 sharing) - Airtime Utilization**

**Varying Offered Loads** In this experiment, we vary the offered loads across the two clients. Combinations of offered loads used across the clients are as shown on the x-axis in the results in Figure 4.2(i), Figure 4.2(j), Figure 4.2(k) and Figure 4.2(l). The maximum offered load is limited to 33Mbps because the channel saturates at that value of the offered load when the physical layer rate is 54Mbps. The channel saturates at this slightly higher value than normal since the Madwifi drivers use fast framing optimizations to improve performance within allocated txops. However, this does not affect our evaluation since it is enabled in all measurement cases. The aggregate throughput achieved using SplitAP framework in this case is slightly deteriorated compared to the traditional Vanilla system. This is because LPFC algorithm uses conservative approach and limits airtime of slice 2 (with 33Mbps physical rate) even though the other client is not using its share. We observe that LPFC scheme limits airtime of Slice 2, to ensure better fairness as compared to the vanilla case with no control.

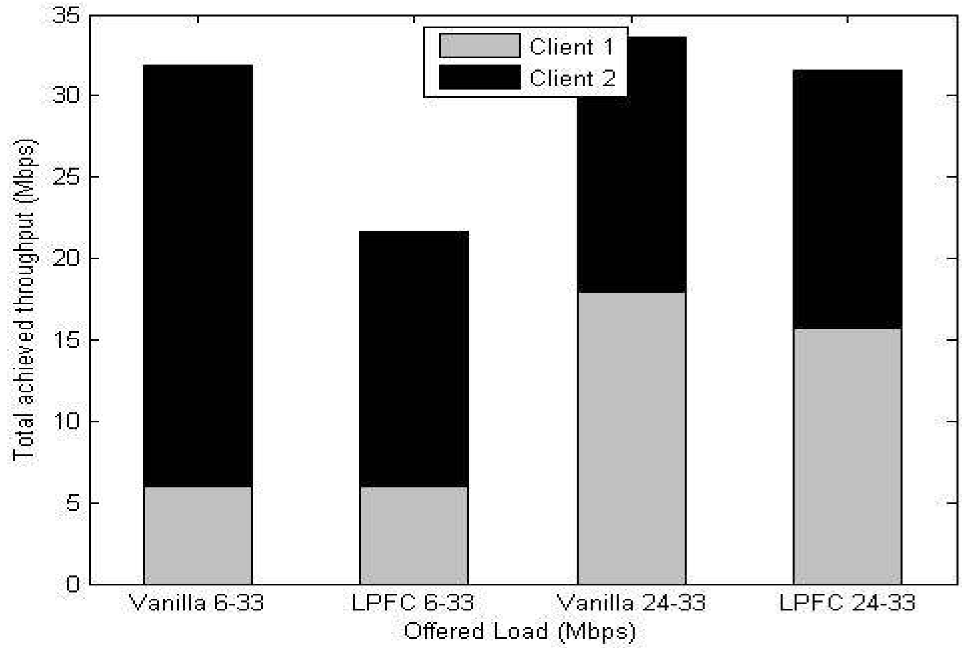


**Figure 4.2(i): Varying offered load experiment (50 – 50 sharing) - Total Achieved Throughput**

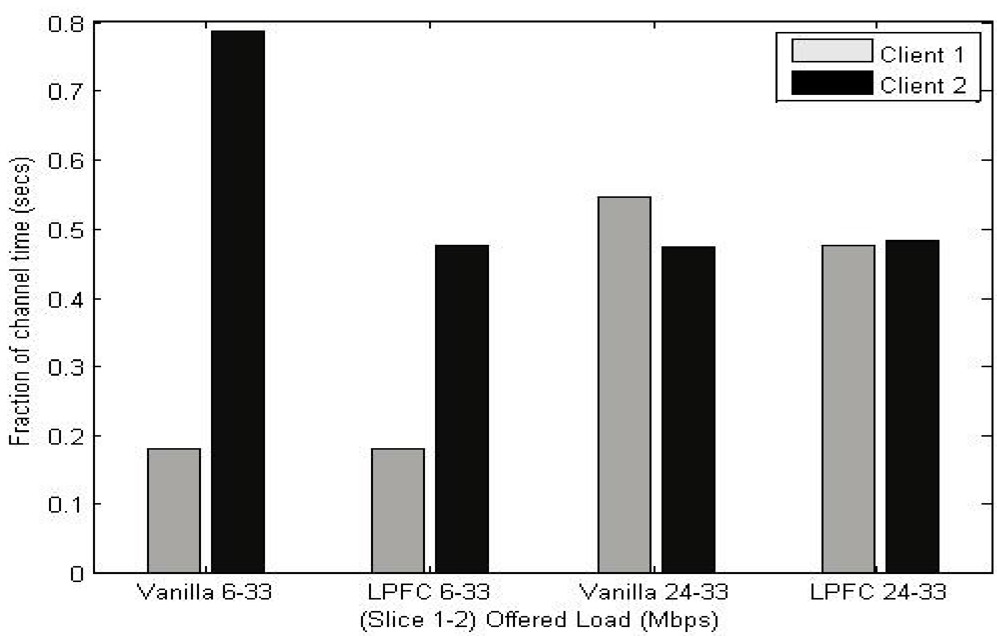


**Figure 4.2(j): Varying offered load experiment (50 – 50 sharing) – Airtime Utilization**

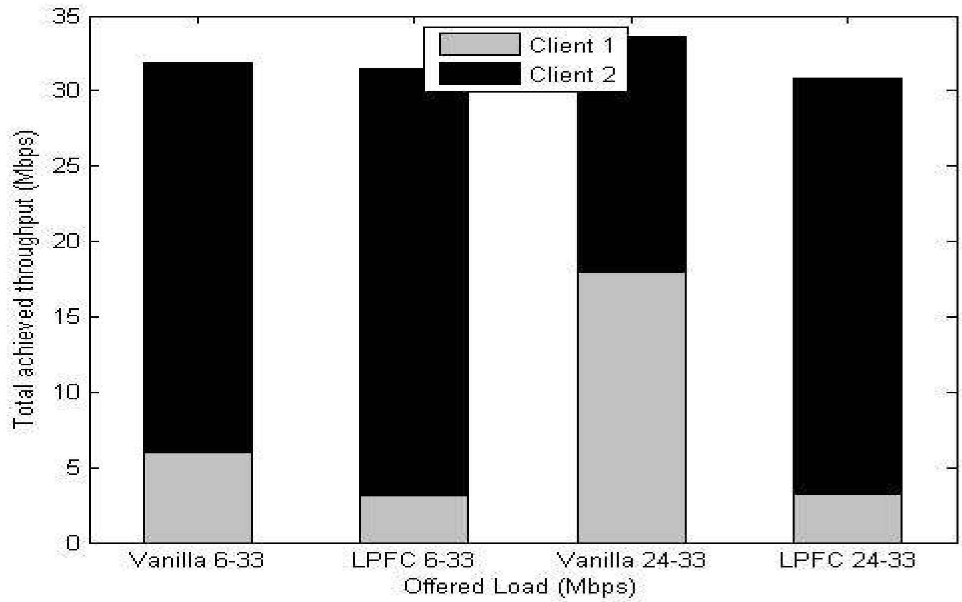


**Figure 4.2(k): Varying offered load experiment (10 – 90 sharing) – Total Achieved Throughput**

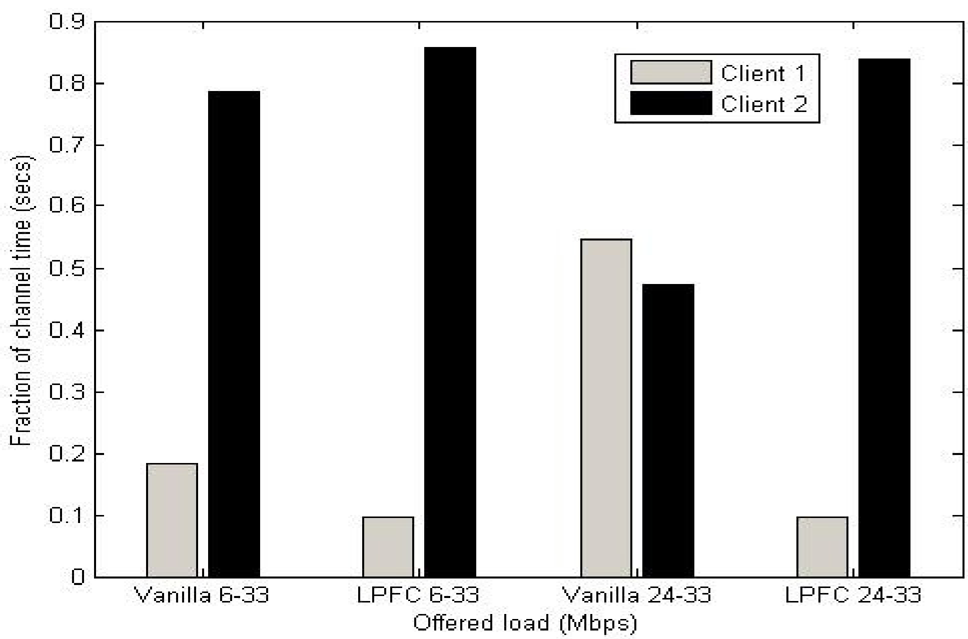


**Figure 4.2(l): Varying offered load experiment (10 – 90 sharing) – Airtime Utilization**

## 4.3 Improvement With LPFC+

Since the LPFC+ algorithm allows the allocation of slice weights such that within a slice we may have varying utilization by independent clients, such a mechanism allows for fair co-existence of transport protocols with different requirements. In this experiment we have two slices: Slice 1 has a client sending constant UDP uplink traffic, while the Slice 2 has two clients. The first client in Slice 2 is sending varying amount of UDP uplink traffic, while the other client in Slice 2 is transferring a 200MB file with a FTP file transfer. Results from this experiment are as shown in Figure 4.3.

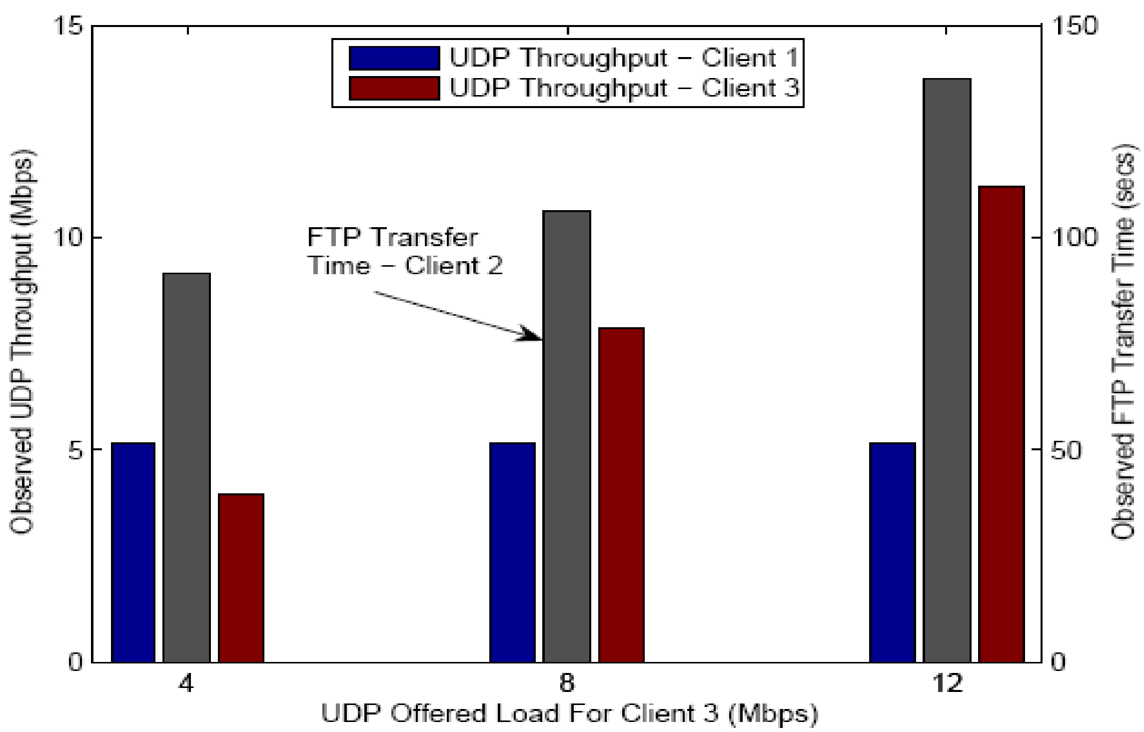


**Figure 4.3: TCP and UDP co-existence in a single slice with LPFC+. Constant UDP traffic of 5Mbps is supported by slice 1, while the Client 2 with FTP transfer and the client 3 with varying UDP loads share the slice 2.**

We observe that the client on slice 1 is not affected despite one of the clients on Slice 2 using UDP traffic. We also observe that the clients on Slice 2 share the UL airtime. When the UDP offered load is less at 4Mbps, the FTP transfer is faster and happens at an aggregate rate of 18.3Mbps. When the UDP offered load on the client increases, the FTP client reduces its rate, thereby requiring longer time for the FTP transfer completion. It is important to note that a similar performance could be achieved even by using *LPFC* instead of *LPFC*+. However, in that case the FTP client on slice 2 would always be limited to a fixed uplink rate thereby resulting in wastage of free bandwidth.

## 4.4 Performance with Real-time traffic using LPFC+

As explained before, since the LPFC+ algorithm allows the allocation of slice weights such that within a slice we may have varying utilization by independent clients, such a mechanism controls the amount of UL and DL traffic load on each slice thus providing isolation between them. In this experiment we have two slices: Slice 1 has a client sending constant UDP uplink traffic of 30Mbps and has slice weight $W_{sliceID}$ = 0.2, while the Slice 2 has two clients with slice weight $W_{sliceID}$ = 0.8. The first client in Slice 2 is sending constant amount of UDP uplink traffic, while the other client in Slice 2 is sending varying amount of UDP uplink traffic in steps of 5Mbps. Results from this experiment are as shown in Figure 4.4.

The realtime performance of the system when client traffic is varying is seen from Figure 4.4. From Figure 4.4 we observe that the throughput of slice 1 remains constant (5Mbps), while within slice 2 the framework tries to accommodate the client 1 as UL UDP traffic from client 2 goes on increasing.

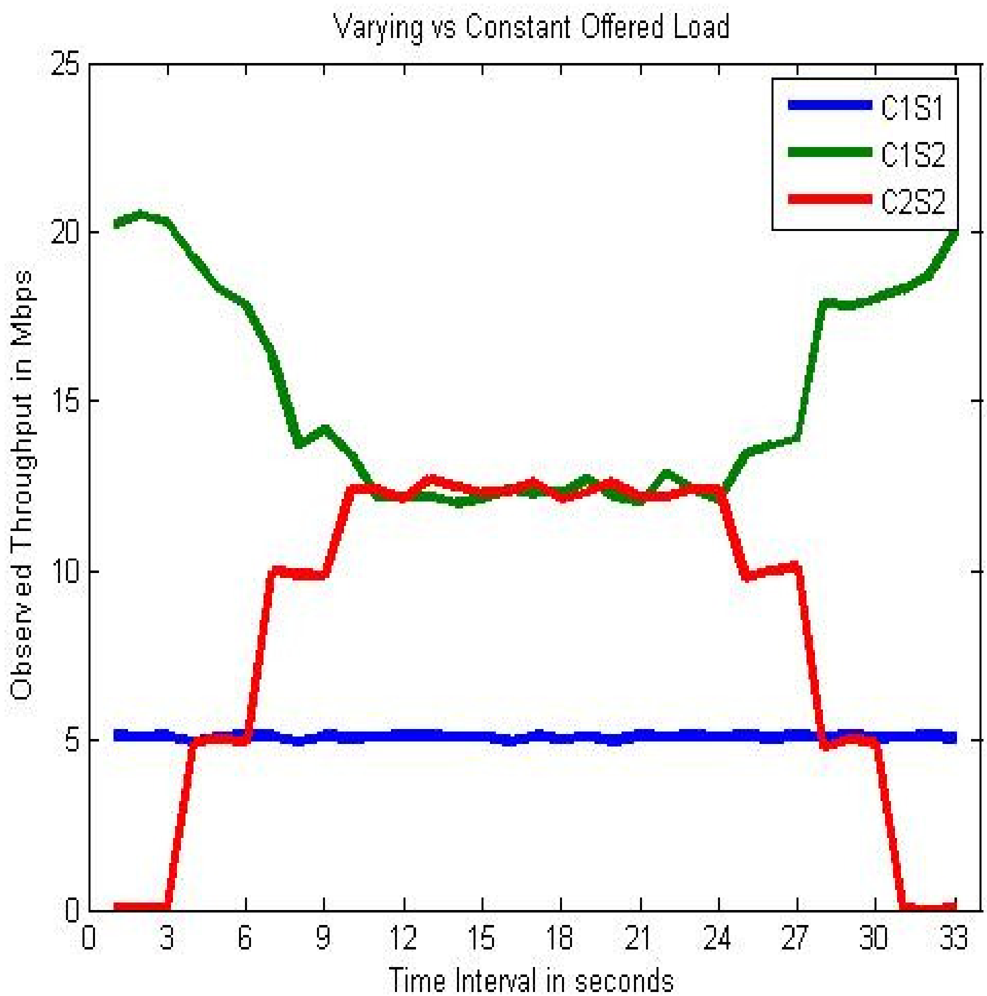


**Figure 4.4: Results for studying performance with realtime traffic using improved LPFC+ algorithm**

## 4.5 Comparison: LPFC Vs LPFC+

In a final experiment we consider a setup with two slices: Slice 1 has a single client pumping UDP UL traffic at saturation, while Slice 2 has 5 clients associated with it. For different experiments, varying number of clients 1 - 5 on Slice 2 will send saturation UL traffic along with the client on Slice 1. In this case we consider the performance of both *LPFC* and *LPFC*+ algorithms, as compared to that without our SplitAP setup (Vanilla).

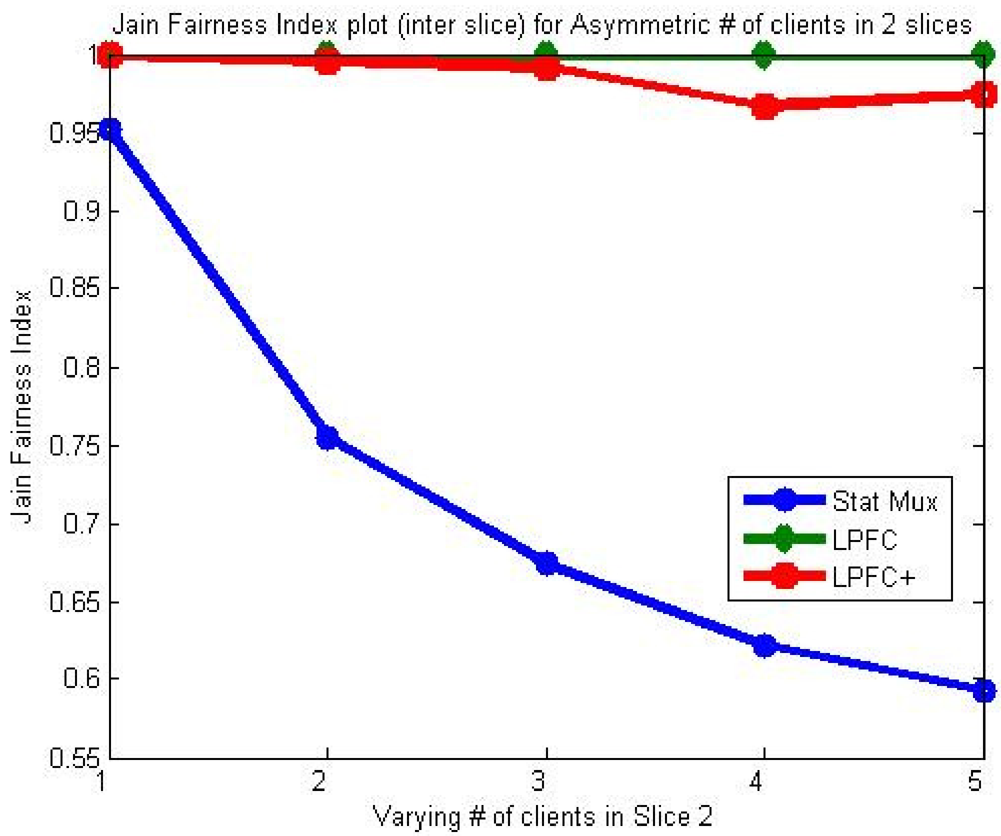


**Figure 4.5(a): Comparison of UL airtime group fairness for: LPFC, LPFC+, and a vanilla system without our SplitAP framework.**

A comparison of the measured modified fairness index is as shown in Figure 4.5(a). We observe that the group fairness index I is always greater than 0.97 with the use of our infrastructure, while it falls down up to 0.6 in a vanilla system without our setup.

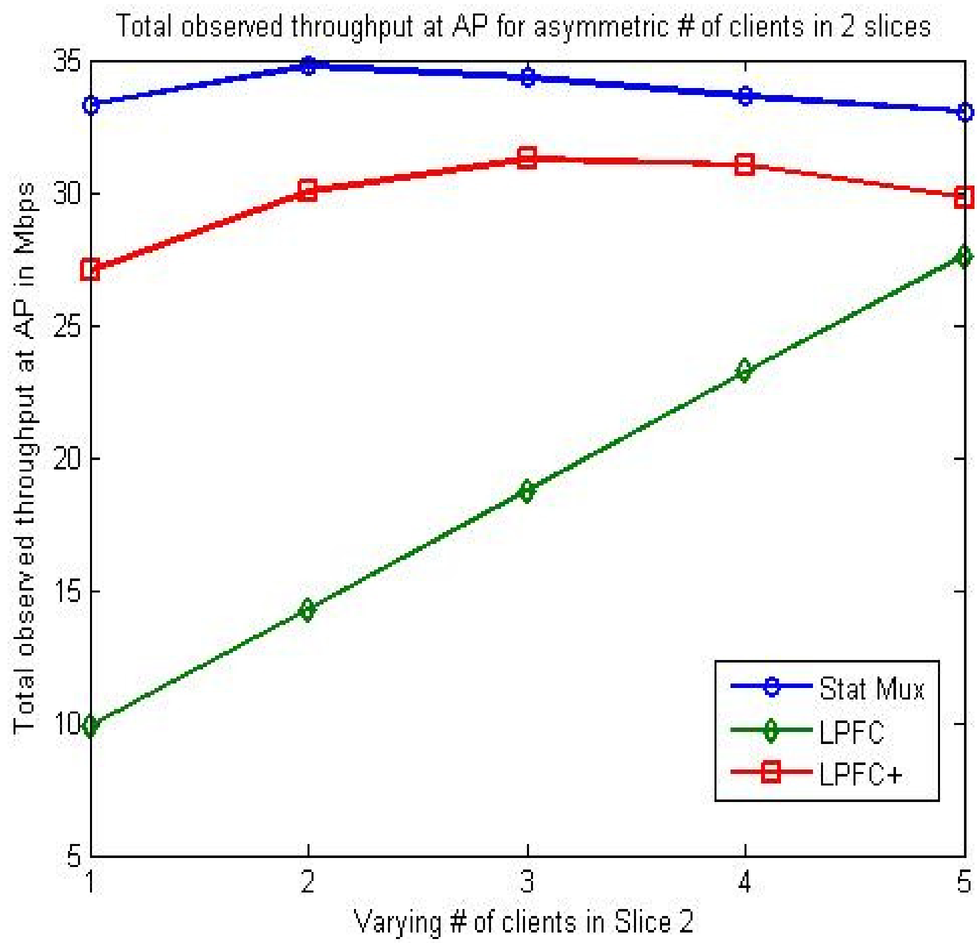


**Figure 4.5(b): Comparison of UL throughput for: LPFC, LPFC+, and a vanilla system without our SplitAP framework.**

The throughput measurements in Figure 4.5(b) show that the improvements in fairness are at the cost of a small decrease in net throughput with *LPFC+*, thus justifying the use of our scheme. The throughput performance with our *LPFC* scheme is less when lesser number of clients on Slice 2 pump traffic. This is because it sees five clients associated with the slice from the beginning, and presents a conservative estimate of $C_{sliceID}$ which results in lower throughput. The *LPFC*+ scheme on the other hand dynamically measures airtime for every slice and adapts its *CsliceID* resulting in better performance. It cannot reach channel capacity since it keeps a 15% tolerance, but is able to divide the remaining airtime fairly. The 15% tolerance value to prevent the system from reaching channel capacity was selected since we achieved best performance on our SplitAP framework with this value while minimizing the wastage of bandwidth based on the extensive experimental evaluation we carried out.

# CHAPTER 5

# CONCLUSIONS AND FUTURE DIRECTIONS

This study discusses the design of the SplitAP architecture that allows the operator to deploy a shared physical access point, which is capable of running algorithms that control UL airtime across user groups. We demonstrate the feasibility of the proposed architecture by implementing the *LPFC* and *LPFC*+ algorithms on a prototype. Results obtained from the measurements on the ORBIT testbed show a significant improvement in the group airtime fairness, while resulting in marginal degradation of overall system throughput.

Future directions include search for more efficient algorithms that can be deployed on the SplitAP framework. Evaluation of the UL airtime fairness issue for mesh and ad-hoc wireless network topologies needs to be done. But the VAP mechanism for time-sharing of physical wireless access point that we have leveraged in this study will not work in case of mesh and ad-hoc networks. A new distributed control mechanism based on explicit Time Division Multiple Access (TDMA) based scheduler would be required to achieve the airtime fairness for these distributed network topologies as against the current centralized controller with enhanced signaling mechanism. Also, the stand alone client application of SplitAP architecture could be implemented as a web browser plugin to make it platform independent. Finally, the slice airtime quota/weight, $C_{sliceID}$ could be included in the beacons of individual VAPs thereby eliminating the need for a separate signaling mechanism.

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