Cross Layer Feedback Architecture for Mobile Device Protocol Stacks

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by

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To my Father
(Late Shri Thakurdas M. Raisinghani)

Approval Sheet

Thesis entitled **Cross Layer Feedback Architecture for Mobile Device Protocol Stacks** by **Vijay Thakurdas Raisinghani** (01429703) is approved for the degree of Doctor of Philosophy

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CERTIFICATE OF COURSE WORK

This is to certify that Mr. Vijay Thakurdas Raisinghani was admitted to the candidacy of the Ph.D degree in July 2002, after successfully completing all the courses required for the Ph.D Degree Programme. The details of the course work done are given below:

Sr. No.	Course No.	Course Name	Credits
1	IT 620	Seminar	4
2	IT 642	Data Warehousing and Data Mining	6
3	IT 690	Mini Project	10

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Abstract

Applications using traditional protocol stacks (for example, TCP/IP) from wired networks do not function efficiently in mobile wireless scenarios. This is primarily due to the layered *architecture* and *implementation* of protocol stacks.

Cross layer feedback is one of the mechanisms to improve the performance of a layered stack in mobile wireless environments. For example, transport layer retransmissions could be reduced by making it aware of network disconnections or hand-off events. One such optimization is Receiver Window Control.

Since the protocol stack is an integral part of the operating system, any cross layer modification to the stack should not impact its *correctness*, *efficiency* and *maintainability*. An appropriate architecture would help ensure that cross layer modifications confirm to these requirements.

We define the design goals for a cross layer architecture based on our study of the pros and cons of existing approaches to cross layer feedback. We present our architecture *ECLAIR* which addresses these design goals. In ECLAIR we exploit the fact that stack behavior is determined by the values stored in various protocol data structures. Our architecture facilitates easy manipulation of these values stored in the protocol data structures. ECLAIR requires minimal or no modification to the existing protocol stack.

We validate and evaluate ECLAIR through a prototype implementation, of receiver window control, and experiments. To evaluate a cross layer architecture we identify metrics for evaluation against each of the design goals. We identify *time* and *space overhead*, *user-kernel crossing*, *data path delay*, *number of changes to protocol stack* and *number of changes to cross layer optimization* as metrics for the design goals. Our results and analyses show that ECLAIR is an efficient cross layer architecture and is easily maintainable.

To further enhance the efficiency of ECLAIR we propose a *core* sub-architecture. Finally, we also present a design guide for cross layer optimizations using ECLAIR.

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Begin at the beginning and go on till you come to the end; then stop.
- Lewis Carroll

Chapter 1

Introduction

The TCP/IP (Transmission Control Protocol/Internet Protocol [70]) protocol stack has been standardized for connecting to the Internet, using wireline devices (example desktop PCs). This protocol stack is also being deployed on mobile wireless nodes (3G and beyond [37, 76]), to ensure interoperability with the existing Internet. Figure 1.1 shows a typical mobile wireless setup. Wireless nodes in this setup are the base station and the mobile wireless devices.

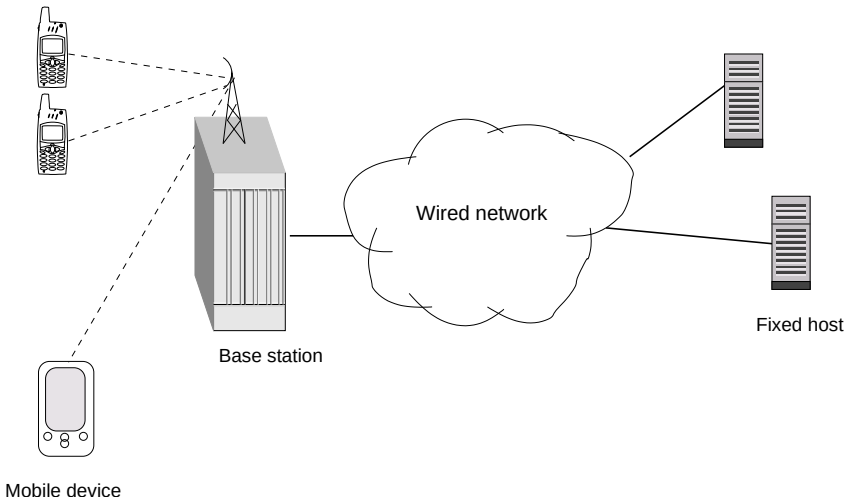

Figure 1.1: Typical mobile wireless scenario

The architecture and implementation of a TCP/IP stack is layered [35]. Figure 1.2 shows a typical TCP/IP stack. In a layered stack, a layer does not share information

about its state with any other layer. For example, layers such as TCP or IP are not aware of disconnection or handoff at the lower layers. This leads to inefficient functioning of the layered stack in mobile wireless environments [75, 85]. On a mobile device, this inefficient functioning would lead to poor user experience, decreased throughput, decreased battery life, etc. We highlight this inefficiency of a layered stack by using TCP as an example.

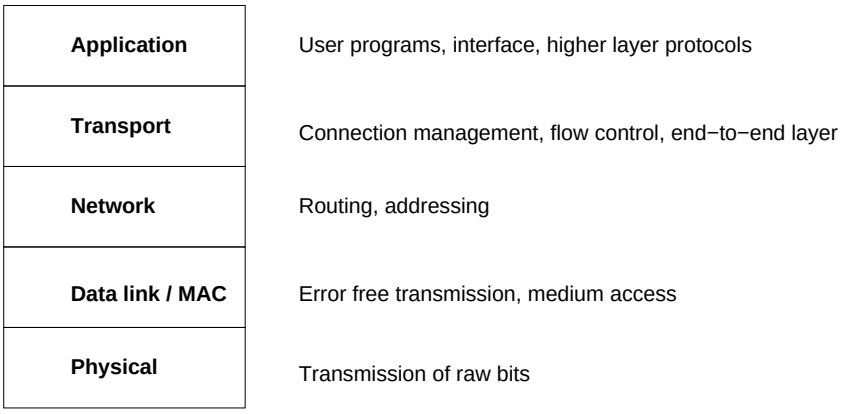

Figure 1.2: TCP/IP protocol stack[74]

Example – TCP over wireless:
TCP is an end-to-end reliable transport protocol [61]. A TCP sender uses acknowledgments from the receiver as a signal to send additional packets. A missing acknowledgment is interpreted as an indication of packet loss due to congestion in the network. However, in mobile wireless environments packet losses could occur due to poor wireless channel conditions and disconnections. Since TCP is unaware of these channel conditions it invokes its *congestion* and *retransmission* algorithms [52, 61]. This response of TCP is inappropriate for mobile wireless networks [75], because it results in unnecessary reduction in TCP throughput. There are various mechanisms for improving protocol stack performance over mobile wireless networks. Some examples for TCP are TCP-Jersey [84], TCP k-SACK [18], I-TCP [6], Snoop [8], early *fast retransmit* [16], TCP-Casablanca [11] and COPAS [24] (for ad hoc networks). A survey of various optimizations for TCP is provided in the references [7, 58, 75].

Cross Layer Feedback:
Out of the various mechanisms for improving TCP, one method is cross layer feedback [30, 38, 43, 65]. If TCP is made aware of the wireless network conditions (information available at lower layers), its behavior could be improved [16, 29]. For example, TCP's congestion algorithms could be adapted or the retransmissions could be controlled using information from the network layer [16]. This information exchange between layers (network layer and TCP in this example) is known as *cross layer feedback*. Using cross layer feedback the performance of layers other than TCP can also be improved (see Chapter 2 for a survey).

Improvements using cross layer feedback have been proposed earlier for wired networks also in references [19, 20, 22].

Cross layer feedback optimizations may be implemented at the intermediate nodes (base station, router, etc – see Figure 1.1) or mobile hosts(MH). Cross layer feedback is not required at the fixed host, since it is not connected to a mobile wireless network. Some of the proposals for cross layer feedback in the intermediate nodes are: snoop [8], channel state dependent packet scheduling [10] and multi-service link layer [86]. Examples of cross layer optimizations which are applicable to the mobile host are Mobile-IP handoff optimization [82] and power management [44].

We focus on cross layer feedback on the mobile host. Our reason is as follows: if cross layer feedback is implemented on an intermediate node (example, base station), then that node would have to maintain the state for each of the connections passing through it. Further, a base station supports a wide variety of devices (example, laptops, handheld mobile devices, etc.), each one having a different wireless environment and resource characteristic. Thus, it would be difficult to implement adaptation suited to each device, in an intermediate node. Hence, we believe that it would be appropriate to incorporate cross layer optimizations in a mobile device. A mobile device has easy access to the state of its resources, established connections and its wireless environment, as compared to an intermediate node.

Thesis objective

The main objective of this thesis is to enable systematic cross layer interaction within the protocol stack, by defining an appropriate cross layer architecture. We also validate and evaluate the proposed architecture.

In the following sections we present an overview of cross layer feedback (section 1.1), existing approaches to cross layer feedback implementation (Section 1.2), problem definition for this thesis (Section 1.4) and our contributions (Section 1.6).

1.1 Cross Layer Feedback

Cross layer feedback means interaction of a layer with any other layer in the protocol stack. A layer may interact with layers above or below it. We list a few examples of cross layer feedback for each layer:

- **Physical:** Channel condition (example, bit-error rate) status from the physical layer can be used by the link layer to adapt the frame length [26]. Also, physical layer transmit power can be tuned by Medium Access Control (MAC) layer to increase the range of transmission [47].

- **Link / MAC layer:** The number of retransmissions at the link layer can serve as a measure of channel condition. TCP may re-estimate its retransmission timers based on this data. The link layer may adapt its error correction mechanism based on the Quality-of-Service (QoS), that is, acceptable delay, packet losses, etc. requirements of the application layer [86].

- **Network:** Mobile-IP hand-off begin/end information can be used at TCP to manipulate its retransmission timer [16]. Mobile-IP layer could use link layer hand-off events to reduce its hand-off latency [67, 82].

- **Transport:** Packet loss data from TCP can help the application layer adapt its sending rate. Link layer and TCP retransmission interference [25] can be reduced by making the link layer adapt its error control mechanisms based on TCP retransmission timer information.

- **Application:** An application could use information about channel conditions from the physical layer to adapt its sending rate [49]. Also, an application could indicate to the user the throughput it requires versus the available throughput.

- **User:** A user may define application priorities which can be to mapped to proportional *receiver window* values within TCP [54, 66].

Besides the feedback between protocols at different layers, as indicated above, feedback could also be between protocols within the same layer. This would be required in scenarios such as *vertical hand-off* [14], when a mobile device moves across heterogeneous networks. In such scenarios, multiple interfaces and hence protocols within the same layer, for example 802.11 [33] and GPRS [48] protocols within MAC and Physical layers, would need to coordinate the hand-off.

As new wireless networks are deployed, various cross layer feedback optimizations would be required to enhance the performance of the existing protocol stacks. These cross layer optimizations would require easy integration with the existing stack. Thus an appropriate architecture is required for implementing cross layer feedback. In the following sections, we present an overview of existing approaches to cross layer feedback implementation and list the proposed design goals for a cross layer architecture.

1.2 Cross Layer Feedback Implementation

1.2.1 Existing Approaches to Cross Layer Feedback

- Physical Media Independence [34] focuses on lower to upper layer feedback. Adaptation modules are created that propagate event information upwards layer by layer.

- Sudame et al [73] use ICMP (Internet Control Message Protocol) messages for propagating lower layer event information to a special handler at socket layer. The adaptation is defined by the application layer.

- MobileMan [21] proposes creation of a new *Network Status* entity which is used for sharing network information with all the protocol layers. Protocols need to be changed to use this network information.

- Carneiro et al [17] propose a *Cross Layer Manager* which contains management algorithms. This manager interacts with the protocol stack for cross layer adaptation.

- Cross LAyer Signaling Shortcuts (CLASS) [79] proposes direct interaction between the layers for cross layer adaptation.

- Interlayer Signaling Pipe [81] uses the packet headers to pass adaptation information to lower layers. The layers read the information in the header and adapt accordingly.

- Mehta et al [54] propose user-space implementation for Receiver Window Control. The adaptation is done in user-space and operating system APIs are used for adapting the transport protocol.

Limitations of Existing Approaches

Efficiency would be lower in architectures such as ICMP Messages [73], PMI [34] and ISP [81]. Communicating cross layer event information in ICMP messages would increase the event communication overheads. In PMI [34], the event information propagates layer by layer which would decrease the cross layer execution speed. In ISP [81] the overhead of scanning each packet and adaptation would slow down the execution of the lower layers and thus reduce throughput, while ICMP Messages [73] would add the overhead of ICMP packet headers. In MobileMan [21], replacing the standard protocol with a redesigned protocol would lead to increased implementation efforts, in case the protocol needs to be changed. Further, the multiple protocols may need to be updated in case *Network Status* component is enhanced. In CLASS [79] each protocol directly interacts with another protocol. This would lead to decreased execution efficiency and portability issues. Implementations based on MobileMan, CLASS, ISP or ICMP Messages would not be easily portable or maintainable since they require modifications to the protocol stack. Lastly, there is no provision for any-to-any layer event communication in either PMI [34], ICMP Messages [73] or ISP [81]. We discuss existing approaches and their limitations in Chapter 2.

1.3 Cross Layer Feedback Architecture Design Goals

From the software engineering perspective cross layer feedback is essentially a modification to the existing protocol stack. An architecture should enable efficient cross layer feedback and also ease the development, deployment and maintenance of various cross layer optimizations. We studied the existing cross layer feedback implementation approaches and their pros and cons. We concluded that the *ideal* cross layer feedback architecture should facilitate efficient cross layer feedback and enable easy maintainability of the cross layer algorithms and the protocol stack. From our analysis we define the following design goals for a cross layer feedback architecture:

- *Efficiency* – to ensure minimum execution overheads
- *Minimum intrusion* – to ensure minimum changes to the existing stack
- *Rapid prototyping* – to enable easy deployment of new cross layer feedback optimizations
- *Portability* – to enable porting to multiple operating systems with minimum changes
- *Any to any layer communication* – to allow communication between a layer and any other layer in the stack.

In the next section, we present the problem defined for this thesis.

1.4 Problem Definition

The objectives of this thesis are to

- *Define a Cross Layer Architecture:* As noted above, existing approaches to cross layer feedback do not address all the design goals of a cross layer architecture. Hence, our primary goal is to define an architecture that addresses all the design goals.
- *Implement and validate the architecture:* Once the architecture is defined, our next objective is to create a prototype and validate it to demonstrate that the architecture can be used for cross layer feedback.
- *Evaluate the architecture:* Our final objective is to compare the proposed architecture with existing approaches. For this, we shall define suitable metrics for each of the design goals.

1.5 Solution Outline

We make the following observations regarding adaptations using cross layer feedback. The adaptation at a layer, when it receives cross layer feedback, may be

- *synchronous* – embedded within the protocol's algorithm, or
- *asynchronous* – executed in parallel to the protocol's execution.

Further, the adaptation may be required for

- *each packet* – protocol adapts behavior for each packet
- *per flow* – separate adaptation is done for each established connection, or
- *across flows* – common adaptation is done for all the established connections.

This defines the granularity of adaptation. Per packet is the finest granularity while across flows is the coarsest. Hence, per packet adaptation can be used for per flow or across flows adaptation also. However, per flow or across flows adaptation cannot be used for per packet adaptation. We describe the types of adaptations in detail in Chapter 2, Section 2.5.1.

In view of the architecture design goals and the types of adaptations, we feel that the ideal architecture should be asynchronous and should not enforce per packet adaptation. This is because per packet adaptation or synchronous adaptation would lead to decreased stack performance. We propose our architecture ECLAIR which satisfies these conditions.

Figure 1.3 shows an overview ECLAIR. The main components are *Optimizing Sub-System* (OSS) and *Tuning Layers* (TL). OSS contains many *Protocol Optimizers* (POs).

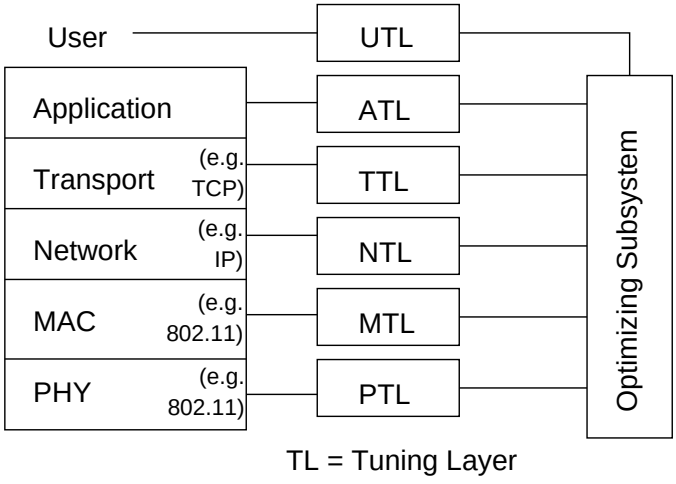

Figure 1.3: ECLAIR architecture

A PO contains a cross layer algorithm. TLs provide the necessary APIs to POs for interacting with various layers and manipulating the protocol data structures.

POs receive *event notifications* from various TLs and decide the *optimizing action* for a protocol. The optimizing action could be to reduce power consumption or reduce packet losses, etc. Optimizing actions modify the protocol stack's behavior. POs manipulate the values stored in the protocol data structures so as to modify the protocol stack behavior (Chapter 3, Section 3.2) .

1.6 Contributions of this Thesis

- *Cross layer architecture design goals* (chapter 2): We analyze the requirements of cross layer feedback and identify design goals for a cross layer feedback architecture.

- *ECLAIR: Efficient Cross Layer feedback Architecture* (Chapter 3): we propose an architecture – ECLAIR – for cross layer feedback. We show that ECLAIR satisfies the design goals of a cross layer architecture.

- *ECLAIR implementation and validation* (chapter 4): We use Receiver Window Control (RWC) [54, 66, 69] (Section 4.1) as a running example throughout the thesis. We use this to illustrate a prototype implementation of ECLAIR, in Linux. We use this prototype to validate ECLAIR.

- *Cross layer architecture evaluation metrics* (Chapter 5): We define performance metrics suitable for evaluation of a cross layer feedback architecture. We use these metrics to compare ECLAIR and existing cross layer implementation approaches.

- *ECLAIR evaluation* (Chapter 5): We not only carry out a qualitative evaluation of ECLAIR but also a quantitative evaluation, including overhead measurement. We instrument the kernel with trace tools such as MAGNET [103] to show that ECLAIR imposes minimal overheads on the protocol stack.

- *ECLAIR sub-architecture* (chapter 6): We propose a sub-architecture *core* for selecting optimal *cross layer data items* for maximizing cross layer feedback benefit and further reducing ECLAIR overhead.

- *Cross layer design guide* (chapter 7): We present a simple technique for selection of the appropriate cross layer architecture, based on the adaptation requirements and the cross layer implementation requirements. We also provide a Linux specific design and implementation guide for appropriate use of ECLAIR for cross layer feedback implementations.

1.7 Organization of Thesis

In Chapter 2 we present the motivation for cross layer feedback architecture and discuss related work. In Chapter 3 we present our architecture for cross layer feedback – ECLAIR. We present ECLAIR implementation and validate the implementation in Chapter 4. We use receiver window control as the running example. In Chapter 5 we define appropriate performance metrics for cross layer feedback and use them for the evaluation of ECLAIR. We compare ECLAIR with other cross layer mechanisms proposed in literature. We also measure the overheads of ECLAIR using kernel trace tools such as MAGNET [103]. We propose a sub-architecture for cross layer feedback in Chapter 6 which helps maximize the benefits of cross layer feedback and further reduce ECLAIR overheads. We present a design guide for using ECLAIR in Chapter 7. We summarize the thesis and present future work in Chapter 8.

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Man is not born to solve the problem of the universe, but to find out what he has to do; and to restrain himself within the limits of his comprehension
- Johann Wolfgang von Goethe

Chapter 2

Motivation and Related Work

In this chapter we motivate the need for cross layer feedback and cross layer feedback architecture. We present a survey of cross layer feedback proposals. We also discuss existing approaches to cross layer feedback implementation. We analyze their drawbacks and propose design goals for a cross layer feedback architecture.

2.1 Introduction

In the previous chapter we presented the performance issues of a layered protocol stack on mobile wireless networks [75, 85]. Since the layers do not interact with each other, the stack functions inefficiently over mobile wireless networks. This leads to poor user experience, throughput and battery life of the mobile device. Cross layer feedback is one of the mechanisms to improve performance of a layered stack, in mobile wireless environments [30, 38, 43, 65]. To improve the performance of the device, cross layer feedback can be implemented within the base station (or router) [8, 10, 86] or the mobile device [82, 44]. However, base stations would need to ensure separate adaptation for each of the devices connected to it. Thus implementing cross layer feedback on the mobile device would be a better option. Hence we focus on cross layer feedback within the mobile device only.

Cross Layer Feedback Simulations:
Our simulations also confirm the benefits of cross layer feedback. This is discussed in Chapter 4. In our experiment, the user defines application priorities which are mapped

to TCP specific parameter, that is, *receiver window* [66]. When the receiver window is decreased, the throughput of the low priority application decreases. This leads to increased throughput for the high priority application.

In Section 2.2 we discuss the various cross layer feedback possibilities and potential benefits. In Section 2.3 we discuss the existing approaches to cross layer feedback implementation and their limitations. In Section 2.5 we present the design goals for a cross layer feedback architecture.

2.2 Cross Layer Feedback

Cross layer feedback means interaction among the layers of a protocol stack. As stated earlier in Chapter 1, Section 1.1, cross layer feedback can be categorized as follows:

- *Upper to lower layers:* This is information flowing downward from a layer to any layer below it.

  Some examples are: application requirements (acceptable delay or acceptable packet losses) communicated to the link layer to enable the link layer to adapt its error correction mechanisms; user defined application priority communicated to TCP to increase the receiver window of the application with a higher priority.

- *Lower to upper layers:* This is information flowing upward from a layer to any layer above it. Some examples are: TCP packet loss information given to the application layer so that the application can adapt its sending rate; physical layer information about bit-error rate and current transmit power communicated to the link/MAC layer which uses this information to adapt its error correction mechanisms or manipulate physical layer transmit power.

Next, we present examples of cross layer feedback for each layer and its interactions with upper and lower layers. We also discuss the benefits and indicate some of the disadvantages.

2.2.1 Physical Layer

The function of physical layer is to transmit raw bits over a certain distance with minimum bit errors, using a suitable power level.

The information available at the physical layer is: transmit power, bit-error rate [1] and coding/modulation in use.

Interaction of Physical layer with upper layers:

[1] For *explicit* measurement of bit-error rate the receiver will have to provide feedback to the sender.

Application or user: The application layer or the device user may tune the physical layer parameters to improve throughput or download software for another physical layer [1]. (see Section 2.2.5 also). However, one disadvantage is that software downloading itself could consume high amounts of power.

Network: The bit-error rate on an interface could be used as a guide by the network layer to select the appropriate interface.

Link/MAC: Ebert and Wolisz [26] discuss *protocol harmonization* for MAC and physical layer for IEEE 802.11 [33]. They investigate the effects of packet length, transmit power and bit-error rate. Their results show that minimum energy is consumed for transmission if an *optimal* transmit power is used for a packet. Further, this optimal transmit power is proportional to the packet length. Also, they show that varying the packet length according to the BER also helps reduce energy consumption. They report that fragmentation into packets of size 500 bytes for a BER $> 10^{-5}$ leads to the largest reduction in energy consumption. (also see Section 2.2.2).

Battery aware physical layer: The physical layer may also adapt its coding/modulation depending on the battery status.

2.2.2 Link / MAC Layer

The functions of link/MAC layer are: improving link reliability through forward error correction (FEC) and Automatic Repeat reQuest (ARQ); avoiding/reducing collisions; fragmenting data into frames so as to ensure reliable transmission with minimal overhead.

The information available at the link/MAC layer is: current FEC scheme, number of frames retransmitted, frame length, point in time when the wireless medium is available for transmission and hand-off related events.

Interactions of link/MAC layer with upper layers:

User: Link throughput information can indicate to the user the kind of application performance that should be expected. The user may then decide which applications can be run.

Application: At the link/MAC layer the frames from different applications may be treated differently. For example, frames of applications with a low delay requirement may be transmitted on priority. Similarly, FEC/ARQ may be improved for applications with a high reliability requirement. The above is based on the idea of a *multi-service link layer* [86], for QoS (Quality of Service i.e. delay, loss, jitter requirements of applications) in the Internet, which adapts the link layer services based on the traffic class. However, such schemes may increase the processing overhead and hence power consumption.

Transport: When channel conditions are poor, retransmission at the link layer results in delays which could lead to TCP retransmissions and thus reduced throughput [25]. To avoid this, TCP and link layer could exchange retransmission information. In an IEEE

802.11 [33] environment increasing MAC level retransmissions to avoid TCP retransmissions, decreases the power consumption [55].

Network: Mobile-IP [59] is used for IP hand-off whenever the mobile device changes sub-nets. Hand-off in Mobile-IP depends on the detection of a network change at the IP layer. This information may not be available as quickly as the signal strength changes monitored continually at the link layer. Thus, link layer hand-off information can be used to reduce the hand-off latency for Mobile-IP [67, 82]. On similar lines, IP micro-mobility protocol, Cellular-IP [77] uses signal strength of the base station beacons for hand-offs.

Interactions of link/MAC layer with lower layers:

Physical: Based on current channel conditions the error control mechanisms at the link layer may be adapted to reduce the transmission errors [47, 50]. Lettieri and Srivastava [47] show around 50% improvement in goodput and 20% improvement in transmission range by using the optimal Maximum Transmission Unit (MTU) for a particular BER. In a GSM case study, Ludwig et al [50] show that by increasing the frame length the throughput can be increased by 18-25%, depending on the radio conditions.

Automatic transmission rate is useful to increase the application throughput by exploiting the functionality available in multi-rate devices. Kamerman and Monteban [39] propose Automatic Rate Fallback (ARF). ARF is a rate adaptation algorithm, which uses information about packet transmission successes to determine the transmission rate. After one or two consecutive packet transmission failures, the transmission rate is decreased and a timer is started. When the timer expires or ten successful acknowledgements are received, the transmission rate is increased to the next higher level and the timer is reset. Holland et al [32] propose Receiver Based Auto Rate (RBAR). In RBAR the sender and receiver exchange (Request To Send/Clear To Send) RTS/CTS packets before transmission. The receiver determines the transmission rate based on a known channel model and the signal-to-noise ratio for the received RTS. Adaptive ARF (AARF) is proposed in reference [45]. For tuning physical layer power see Section 2.2.1.

Battery aware link/MAC layer: see Section 2.2.1 for optimization in collaboration with physical layer.

From the examples in the previous sections, it can be seen that adaptation of error control mechanisms at the link/MAC layer along with transmit power control at the physical layer can help in substantial reduction in power consumption and improvement in throughput.

2.2.3 Network Layer

Network layer functions are routing, addressing, selecting the network interface, and IP hand-off [59] to maintain IP connectivity in *foreign* networks.

The information available at the network layer is: Mobile-IP hand-off initiation/completion events and the network interface currently in use.

Interactions of network layer with upper layers:

Application or user: An application could control its sending rate based on Mobile-IP hand-off indications.

A device may have multiple wireless network interfaces that can provide different levels of service. For example, a wireless LAN interface may provide lesser delays and higher throughput as compared to a GPRS interface on the same device. Depending on the application or user needs, the network layer could select an appropriate network interface. However, continuing a session uninterrupted onto another interface is an open research area.

Transport: Mobile-IP hand-off delay may lead to reduced throughput due to the TCP retransmission time-out and back-off mechanism. TCP can be informed about the event of Mobile-IP hand-off to reduce the retransmission latency. A *fast retransmit* [16] can be initiated on the mobile host using this information. Depending on the hand-off conditions, this helps in reducing TCP retransmission latency by upto 75% and improving throughput by upto 25% [16].

Interactions of network layer with lower layers: *Link/MAC:* see Section 2.2.2; *Physical:* see Section 2.2.1.

From the aforementioned, it seems that the Mobile-IP hand-off indications to the application and TCP would be quite useful in conserving the battery and increasing throughput.

2.2.4 Transport Layer

The transport layer is concerned with establishing end-to-end connections over the network. Mobile networks are characterized by large delays, packet losses and high bit error rates. Transport protocols like TCP interpret this as a congestion loss which reduces its throughput [16]. Cross layer feedback may also be beneficial in case of protocols like Universal Datagram Protocol (UDP) or Real-time Transport Protocol (RTP) , however we restrict our discussion to TCP.

The information available with TCP is: round-trip time(RTT), retransmission time-out(RTO), maximum transmission unit (MTU), receiver window, congestion window, number of packets lost and actual throughput (or goodput).

Interaction of transport layer with upper layers:

User: A user may assign priorities to the running applications. In case the applications are downloading some data, this higher priority would indicate the need for higher download bandwidth. To enhance user satisfaction, TCP may map the higher priority of an application to a larger receive window [66, 64]. Further, a user could provide in-

formation about an impending disconnection. This information can be used by TCP to increase its RTO values (also see Section 2.2.6). Also, TCP may provide packet loss and goodput information to the user. The user may shutdown some non-critical applications based on this input, which would help improve user experience.

Application: Applications may indicate their QoS requirements to TCP. Based on this information TCP may manipulate the receiver windows. On the other hand, TCP may provide packet loss and goodput information to the application. The application can use this input to adapt its sending rate.

Interaction of transport layer with lower layers: *Network:* see Section 2.2.3; *Link/MAC:* see Section 2.2.2

2.2.5 Application Layer

The application layer is the interface to the user for running user tasks. For example: web browsing, downloading a file using FTP, sending e-mail, watching a video clip, etc.

The existing applications were designed for wired networks and do not perform well in wireless networks. Application adaptation based on information from lower layers would be useful in improving application performance over wireless networks.

An application layer can communicate to other layers the application's QoS needs i.e. the delay tolerance, acceptable delay variation, required throughput and acceptable packet loss rate.

Interaction of application layer with upper layers:

User: A user's requirement can be captured by an application and communicated to the lower layers. The mobile device could then be re-configured to satisfy user needs [1].

Interaction of application layer with lower layers:

Transport: see Section 2.2.4; *Network:* see Section 2.2.3; *Link/MAC:* see Section 2.2.2.

Physical: Multi-media applications like video, use various standard coding techniques for video transmission. Information about channel conditions can be used to adapt the coding. For example, if the bandwidth is low, a lower quality video coding may be used which requires lesser bandwidth. Similarly, an email application could defer downloading the file attachments in an email when the channel conditions are poor. Some of the proposals for application adaptation are [3, 49, 56]

Power saving based on application information: If the application can tolerate some delays, it may be possible to switch off the network interface card intermittently [44]. Information about the type of coding used by a video-application could be used to discard some frames at the network interface to save power [2]. However, this will reduce the video quality.

The discussion above indicates that information about channel conditions, from the physical and link/MAC layers, would be useful in improving application performance.

Also, tuning the link layer error control mechanisms based on the application QoS requirements, seems to be essential in improving application throughput.

2.2.6 User

We believe that improving user satisfaction is the ultimate goal of improving application performance on wireless devices. Cross layer feedback on a mobile device would help in improving application performance and thus user satisfaction. However, to further enhance user satisfaction it is essential to incorporate dynamic user requirements

We consider the user to be the uppermost layer of the protocol stack. We believe that user requirements should be taken into account to enhance *user perceived QoS*. The motivation for this is that the user decision could be contrary to the system decision but it could lead to improved user satisfaction. For example: (1) for a user a FTP download may be more important than a streaming video, (2) a user may know that a disconnection is imminent in an approaching tunnel while the system will *know* it only after the signal is affected, (3) the system may decide to conserve battery by not downloading some information while the user may, at that instant, feel that the information (e.g. a *stock quote*) is more important than saving battery.

The user will need information from the lower layers to use the mobile device effectively. It seems that the most crucial one will be link throughput information from the link layer. This will help the user decide about the applications that can be run and also indicate to the user the kind of performance that should be expected.

Interaction of user with lower layers: *Application:* see Section 2.2.5; *Transport:* see Section 2.2.4; *Network:* see Section 2.2.3; *Link/MAC:* see Section 2.2.2; *Physical:* see Section 2.2.1

Battery status: Depending on the battery status, the user may instruct the system to optimize power consumption sacrificing performance and vice versa.

Other surveys related to cross layer feedback are as follows: Jones, et al [38] present a survey of work addressing energy efficient and low-power design within all layers of the wireless network protocol stack. Zorzi, et al [89] discuss the impact of higher order error statistics on the various layers of the protocol stack. Power aware protocols in ad hoc networks are discussed in reference [30]. References therein provide insight into the various power aware protocol proposals and design issues. Badrinath, et al [5] present a conceptual framework for network and client adaptation. They survey the various proposals for application adaptation and map it to the conceptual framework.

In this section we presented the different possibilities of cross layer feedback with a discussion about the benefits. Our experiments with user feedback also confirm the benefits of cross layer feedback [66]. Table 2.1 summarizes the cross layer research presented above. Table 2.1 shows the various cross layer feedback possibilities. Layers which are

information *producers* are shown in the left most column and layers which are information *consumers* are shown in the top most row. The table cells contain the information created by producers and used by consumers, along with relevant references. For example, Physical layer (information producer) has information about channel conditions and signal strength. This information can be consumed by the MAC layer to adapt the packet frame length [50]. *User* and *Battery/Power/Energy* are shown in parenthesis to distinguish them from protocol stack layers. In the next section we discuss the various approaches to cross layer feedback.

2.3 Existing Approaches to Cross Layer Feedback

2.3.1 Physical Media Independence

One of the early proposals is the Physical Media Independence (PMI) [34] architecture, by Inouye et al. The primary focus of this architecture is informing upper layers about changes at the network interface. The aim is that the network configuration of a mobile computer should adapt itself as the interfaces are disabled or enabled.

A set of device characteristics is defined. The characteristics are:

- *Present:* Device is physically attached
- *Connected:* Link-level connectivity
- *NetNamed:* Network name is bound to device
- *Powered:* Power is available
- *Affordable:* Cost of use is within budget
- *Enabled:* User has enabled the device

Together, the above characteristics determine whether a device is *available* or not.

Guard modules are used to monitor the device characteristics. There guard modules are placed in the system in such a way that they can easily monitor the required characteristic. For example, the guard for *Connected* is placed in the device driver. The guard for *Enabled* is created by adding a event mechanism that is triggered whenever the user invokes the operating system API for enabling or disabling the device. The information from all the guard modules is delivered to the *device manager*.

Device related events are propagated to higher layers. This is achieved by *adaptation modules* attached to each layer. The device information is propagated layer by layer. A layer completes its adaptation and then allows the information propagation to higher

Table 2.1: Cross layer feedback possibilities and relevant references

Consumers⟶ Producers ↓	**(User)**	**Application**	**Transport (TCP)**	**Network (IP)**	**Link / MAC**	**Physical**
(User)		- User QoS requirements [1]	- Application priority [66] - Impending disconnection	- Interface selection		- User QoS requirements [1]
Application	- Goodput		- QoS	- QoS [3]	- QoS [3], [86] - Coding [2]	- QoS, Bandwidth request [3] - Power control [3], [44]
Transport (TCP)	- Packet loss / goodput	- Packet loss / goodput			- RTT/RTO information	
Network (IP)			- Hand-off [16] - Interface change [34]		- QoS [46]	
Link / MAC	- Errors [89] - Goodput	- Errors [56, 89]	- Errors [89] - Interface queue [53] - Hand-off	- Errors [89] - Channel condition [53] - Route failure [63] - Hand-off [67], [82] - RTS/CTS [27]		- Errors [89] - Power [26]
Physical		- Bandwidth available [56]		- Capability [12] - Bandwidth [60] - Interface / card removed [34]	- Channel conditions / Signal strength [14, 32, 39, 45, 46, 47, 50, 80]	
(Battery/ Power/ Energy)	- Battery status	[2, 30, 38, 56]	[30, 38]	[30, 38]	[26, 30, 38]	[26, 30, 38]

layers. For example, since the information propagates *upwards* through the stack, IP layer will receive the information earlier than TCP. The information will propagate to TCP only after IP has completed its adaptation.

Policies for adaptation are propagated from upper to lower layers through the adaptation modules.

PMI Limitations

In PMI [34] architecture, the focus is on cross layer feedback about device information to upper layers, that is, lower to upper layers. The device related information is propagated upwards layer by layer. A layer sends the information upwards only after completing its adaptation. This decreases the speed of information propagation.

The architecture also requires modification to the operating system to track *enable/disable* of the device done by the user. Further, operating system calls are used for interacting with the stack. This would increase the efforts required for maintenance of the cross layer implementations. In addition, operating system calls increase execution overheads since user kernel crossing is involved (see Chapter 5 for details).

2.3.2 ICMP Messages

Sudame and Badrinath present a cross layer feedback architecture based on Internet Control Message Protocol (ICMP) messages [73]. The focus of the architecture is to make the stack aware about changes in the network environment.

The network environment is determined by a set of parameters such as latency, bandwidth, energy, cost, signal strength, etc. These parameters are represented as device parameters. The device data structure in the operating system is modified to include these parameters. An API is provided to the kernel and applications to *get* and *set* the parameters of the device. Multiple *watermarks* are used to detect changes in the parameters. A *violation* of a watermark constitutes an event. This event is propagated to higher layers in the stack.

In this architecture, event propagation is achieved through Internet Control Message Protocol (ICMP) messages. The ICMP message may be generated locally or by a remote system. On the host, the message is generated by a daemon or some part of the kernel. A new ICMP message *ICMP_STATUS* is created. A *handler* is implemented for this message. This handler invokes a function at the socket layer. This function in turn notifies the interested applications and determines protocol specific adaptation actions for the other layer, example, TCP.

Interested applications create a datagram socket for communication with the lower layers. An API is provided to enable the applications to register for events of interest.

The application receives events in this socket's buffer. Applications can choose to receive notification of message arrival through operating system *signals*. The application specified events are stored in a table at the socket layer.

For transport layer protocol adaptation, the protocol provides a function (*action*) to adapt the protocol-specific parameters. This parameter change is used to modify protocol behavior. In case a new parameter is required, the protocol implementation is suitably modified. The protocol implementation checks the values of these new parameters also to determine protocol behavior. A protocol's adaptation is restricted by this set of actions provided by the protocol. Applications define the protocol adaptation using the protocol actions. Each application determines the protocol adaptation for itself. Based on the adaptation required by the application, an *action table* is attached to the transport protocol socket being used, by using the operating system call `setsockopt()`. The handler on receipt of the ICMP message, scans the action table and adapts the transport protocol behavior. Subsequently, another table is scanned for interested applications and the events are delivered to the applications.

ICMP Message Limitations

The primary focus of the ICMP messages architecture [73] is on application and transport layer adaptation. While, the application defines the adaptation for transport layer, there is no mechanism for feedback from other layers to lower layers. For example, transport layer information cannot be communicated to the MAC layer. The architecture does not enable any-to-any layer feedback in general. Further, the architecture does not provide a mechanism for defining adaptation for layers below the transport layer.

The architecture requires modification to the protocol stack to introduce application and transport *action* tables and a new ICMP message handler. Further, the protocol layers need to be modified to introduce new APIs in the protocol stack to support adaptation. In addition, the architecture proposes introduction of new *variables* in the protocol to allow modification of protocol behavior. These modifications would lead to difficulty in ensuring protocol correctness and increased efforts for stack code maintenance. Further, the execution overheads of a protocol layer will increase, since additional code will be required for checking the status of new variables introduced in the protocol. The cross layer feedback overhead is higher since the messages are encapsulated in ICMP messages. Lastly, the adaptation of the transport layer is based on the *actions* defined by the application, that is, the transport protocol is adapted for each application separately. There is no mechanism to define a common adaptation for all the transport layer sessions.

2.3.3 MobileMan

Conti et al propose the MobileMan [21] architecture. MobileMan is primarily intended for ad hoc networks. In this architecture protocols belonging to different layers share network-status information. The architecture has a core component called *Network Status*. This component is a repository for all information collected by the network protocols in the stack. Each protocol can access this repository and share information with other protocols. The access to Network Status is standardized. MobileMan recommends replacing the *standard* protocol layer with a redesigned *network-status-oriented* protocol, so that the protocol can interact with Network Status. MobileMan has been deployed on experimental testbeds for ad hoc networks.

MobileMan Limitations

MobileMan architecture requires creation of a *Network Status* component. The architecture requires *substantial* modification to the protocol stack, since it proposes replacement of the standard protocol with a network status aware protocol. This makes it difficult to add new cross layer optimizations to the stack. Also, this introduces a *dependency* between the protocol and the network status component. Whenever the network status component is modified all the protocols using this component need to be modified. Further, the stack processing overhead is increased since the protocol executes additional code for monitoring the network status and determining appropriate action.

2.3.4 Cross Layer Manager

Carneiro et al [17] propose a framework using *cross layer manager*. The protocol layers expose *events* and *state variables* to the cross layer manager. *Management algorithms* are woken up by the *events*. The cross layer manager uses the state variables to query / set the protocol internal state. Four interlayer coordination *planes* are identified viz. security, quality of service, mobility and wireless link adaptation. Internal details of this architecture are not available.

Cross Layer Manager Limitations

The cross layer manager framework [17] requires that the layers generate *events*, which are fed to the cross layer manager. This event generation within the layer would lead to slow down of the layer execution. Further, the cross layer manager is dependent on the protocol implementation since it reads and updates state variable information of a protocol.

2.3.5 Cross Layer Signaling Shortcuts

Wang and Abu-Rgheff [79] propose Cross LAyer Signaling Shortcuts (CLASS). CLASS allows direct interaction between the layers e.g. Application layer can directly interact with the Link layer. When a specific parameter changes within a layer, the layer generates an event. A layer provides *set* and *get* APIs for its parameters. System calls are used to read the message. Details of the mechanism have not been provided.

CLASS Limitations

Cross Layer Signaling Shortcuts [79] primarily aims at increasing the cross layer feedback speed. However, since the cross layer adaptation is built into the layer, the layer needs to be modified for each new cross layer algorithm. Further, a layer generates events for informing other layers. Both of these modifications introduce a processing overhead on the layer, which leads to reduction in the stack processing speed. Since the architecture proposes direct interaction between the layers, it introduces a dependency between interacting layers. This would lead to increased efforts in maintaining the cross layer feedback implementation.

2.3.6 Interlayer Signaling Pipe

Wu et al [81] propose interlayer information exchange using the packet header. This is suitable for cases where some adaptation may be required at lower layers for each packet from higher layers. The information is encoded in the Wireless Extension Header (WEH) of IPv6 packets, to pass the information to intermediate nodes, if required.

ISP Limitations

Interlayer Signaling Pipe [81] is basically for upper to lower layer feedback. Since the information is passed in packet headers, the lower layer needs to be modified to read and parse the packet. Further, the layer needs to take appropriate action based on the information in the packet. This requires additional code execution in the lower layer, which reduces the stack efficiency. In addition, the lower layer is dependent on cross layer information format of the upper layer. This makes the lower layer *dependent* on the upper layer. Any change in a upper layer's cross layer information format will lead to changes in all layers *dependent* on this layer. This mechanism cannot be used easily for lower to upper layer feedback, since the packet headers are stripped as the packet moves upwards. Further, modification to the packet header could lead to check-sum errors. Lastly, this mechanism cannot be used for feedback from a layer to any other layer without passing the message through the intermediate layers.

2.3.7 User-Space Implementation

Mehra et al [54] propose user-space implementation of a cross layer feedback optimization (Receiver Window Control [54, 66]). The cross layer algorithm is implemented in user-space. The `read()` system call in *libc* library is modified, so that the algorithm is invoked for each read by an application. Operating system calls such as `getsockopt()` and `setsockopt()` are used to modify protocol parameters.

User-Space Limitations

The protocol adaptation by a user-space implementation is constrained by the API provided by the operating system, that is, the system calls provided for protocol tuning. Thus user-space implementations incur the overhead of user-kernel crossing, that is, some CPU cycles are spent in triggering a soft-interrupt and sending the data from user to kernel-space and vice-versa. If the adaptation code is placed within the path of the protocol data unit, it decreases the stack execution speed.

2.3.8 GRACE

The above examples of cross layer feedback focus on improvements *within* the protocol stack. The *GRACE* (Global Resource Adaptation through CoopEration) framework [88] is aimed at cross layer adaptation across the hardware, software (OS) and application layers. However, GRACE does not address adaptation of any the protocol stack layers.

Approaches such as ICMP Messages [73], MobileMan [21], CLASS [79] and ISP [81] require modifications to the protocol stack for implementing cross layer feedback. However, modifying the protocol stack can lead to problems in execution efficiency and maintainability of the cross layer system. In the next section, we summarize the problems that arise due to modification of the protocol stack.

2.4 Problems with Modifying the Stack

- Each additional cross layer feedback code block in a protocol would slow down the execution of that protocol. This would reduce the throughput of that protocol. If a protocol interacts with many other protocols this would lead to a large reduction in its throughput.
- The cross layer feedback code would have to be rewritten for porting to other operating systems.
- Multiple cross layer optimizations within a protocol could lead to conflicts [41] and hence difficulty in ensuring correctness of the protocol's algorithms.

- Cross layer feedback code once added to a protocol would be difficult to update or remove, since the code would be intertwined with regular protocol code.
- Trial (fast prototyping) of new cross layer feedback ideas would not be easy, since the protocol code would need to be modified.

The above problems are compounded when multiple such cross layer optimizations are implemented. Figure 2.1(a) shows a single cross layer optimization for TCP and MAC interactions. Figure 2.1(b) shows multiple cross layer interactions introduced in the stack.

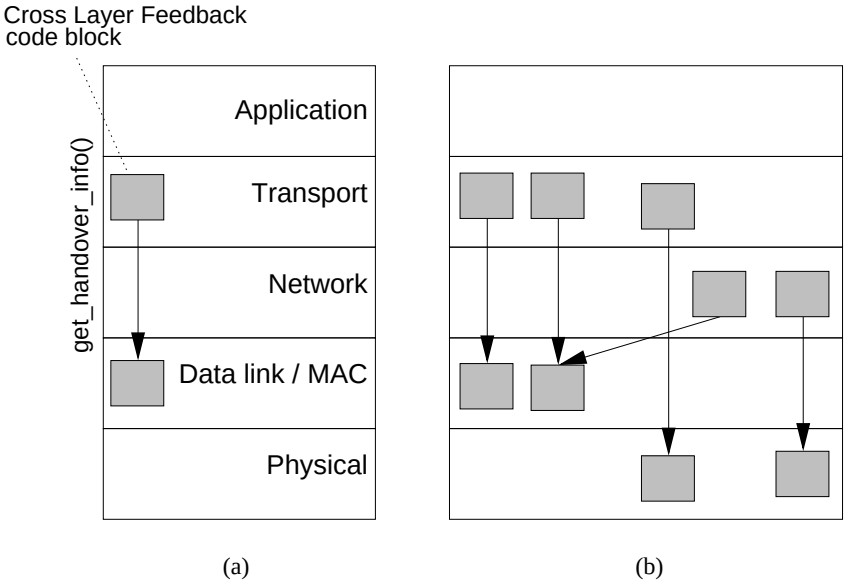

Figure 2.1: Cross layer feedback: Modification to protocol stack

Above we discussed the various mechanisms for cross layer feedback and their limitations. We also highlighted the problems associated with modifying the protocol stack for implementing cross layer feedback. Based on the above discussion, we define the design goals of a cross layer feedback architecture and define the objectives for this thesis.

2.5 Cross Layer Feedback Architecture Design Goals

From the software engineering perspective cross layer feedback is essentially a modification to the existing protocol stack. The stack forms an important part of the kernel. Thus it is important that any modification to the stack:

- imposes minimal overhead on the stack
- does not affect the correctness of the stack
- does not introduce any other errors in the stack

- is easily extensible and reversible if required
- allows feedback from a layer to any other layer in the stack

The above points are explained below:
Imposes minimal overhead on the stack: Any cross layer feedback implementation would entail execution overheads. This execution overhead should be minimal.
Does not affect the correctness of the stack: The correctness of each of the existing protocols in the stack is proven. Any modification to any of the protocols can impact the correctness of the stack. Cross layer feedback aims at modifying the existing protocol stack behavior. It is essential to ensure that cross layer feedback does not lead to incorrect stack behavior. For example, Medium Access and Control (MAC) layer has a certain back-off behavior when a collision occurs. The MAC behavior should not be modified such that the fairness of access to the medium is violated.
Does not introduce any errors in the stack: The stack is a critical part of the operating system. An error in the stack can lead to a crash in the operating system. Errors in the cross layer feedback implementation could lead to a system crash. The cross layer implementation should be able to trap such errors to enable error free execution of the stack.
Is easily extensible and reversible if required: Cross layer feedback implementations would require some maintenance / enhancements in future. Some of the cross layer optimizations may need to be removed or replaced with new optimizations. Thus it is essential that the cross layer feedback implementation can be easily enhanced or removed.
Allows feedback from a layer to any other layer in the stack: To ensure maximum benefit from cross layer feedback, the cross layer feedback mechanism should not restrict the feedback in a particular direction. For example, upper to lower layers or lower to upper lower layers only, or only between a set of layers.

The above requirements are restated in a concise form as the design goals for a cross layer architecture:

- **Efficiency**: Enable *efficient* cross layer feedback. By efficient we mean cross layer feedback which helps attain maximum performance improvement of the stack, with minimal overheads.
- **Rapid prototyping**: Enable easy development and deployment of new cross layer feedback algorithms, independent of existing stack.
- **Minimum intrusion**: Enable interfacing with existing stack without significant changes in the existing stack. This would aid in easily extending or reversing the optimization. This would also help in protecting the correctness of the stack.
- **Portability**: Enable easy porting to different systems.

- **Any to Any layer communication:** Allow cross layer feedback from any layer to any layer i.e. upper to lower layer or lower to upper layer.

The above design goals would help ensure that a cross layer architecture is designed in such a way that it

- enables cross layer feedback with the minimum possible overheads on the system
- allows evolution and maintenance of the cross layer implementation with minimum possible effort

This would help overcome the limitations of the existing approaches to cross layer feedback implementation, as described in Section 2.3.

On receipt of cross layer feedback information, a protocol needs to adapt its behavior. Below we present our observations about the types of adaptation.

2.5.1 Adaptations using Cross Layer Feedback

Asynchronous and Synchronous Adaptations

The adaptive action at a layer, based on cross layer feedback from another layer, may be *synchronous* or *asynchronous*. In synchronous adaptation, whenever a layer receives some cross layer information, it proceeds with its *regular* execution only after executing the cross layer adaptation required. For example, assume there is *network disconnection* event sent to TCP from the link layer. In the synchronous case, TCP's regular execution is stopped, appropriate adaptation is carried out in TCP and then regular TCP execution proceeds. In the asynchronous case, the TCP adaptation would be done in parallel to TCP execution. Further, synchronous or asynchronous adaptation may be required for each packet or a flow.

Adaptations for Packets and Flows

A mobile device may have multiple data sessions with fixed hosts. When a device establishes a connection over the IP network, to some fixed host, a wireless interface is selected and the connection is established over a set of routers. We call this a *flow*. For example, one flow could be over GPRS and another flow could be over WLAN.

We describe cross layer feedback for these cases below:

- *per flow:* The flows, as described above, would have different QoS characteristics, (that is, different delay, throughput and bit error rate). Protocol adaptations for a flow may need to be specific to that flow. For example, TCP timers may need to be set to different values when there is congestion on the network. We call this *per flow* type of adaptation.

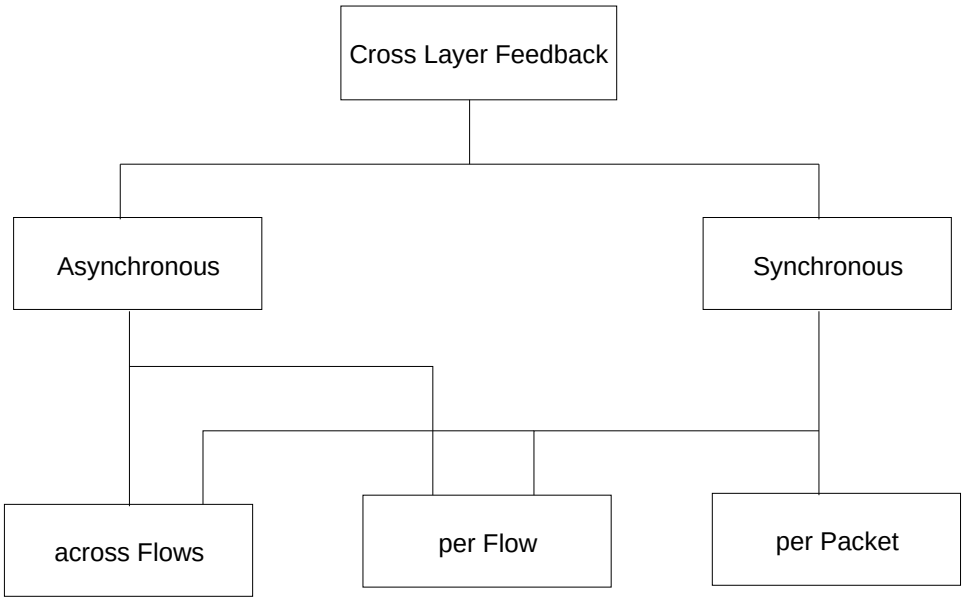

Figure 2.2: Cross layer feedback classification

- *across flows:* On the other hand, the same adaptation may be applicable to all the flows. For example, on disconnection, TCP retransmission timers for all flows may need to be canceled or increased by a constant factor. We call this *across flows* type of adaptation.

- *per packet (similar to snoop [8]):* Besides the above, specific adaptation may be required for each packet. We call this *per packet* adaptation.

Per flow and across flows adaptation can be done in asynchronous or synchronous manner depending on the optimization requirements. However, per packet is synchronous since the adaptation needs to be done as the packet is being processed. Figure 2.2 summarizes the cross layer feedback adaptation types.

2.5.2 Objectives of this Thesis

As stated in Section 1.4, the objective of this thesis is to define an architecture which addresses the design goals stated above, validate the architecture and compare it with the existing approaches.

In Chapter 1, Section 1.5, we presented an overview of ECLAIR, which satisfies the architecture design goals stated above and enables asynchronous adaptation to ensure higher efficiency. In the next chapter, we present the details of ECLAIR.

2.6 Summary

In this chapter we presented a representative survey of existing research on cross layer feedback optimizations. As new wireless networks are deployed, to enhance the performance of the protocol stacks multiple cross layer feedback algorithms would be required. These algorithms would need to be easily integrated with the existing stack.

Introduction of cross layer feedback should not impact the correctness, efficiency, and maintainability of the existing protocol stack. We showed that existing approaches to cross layer feedback implementation impact the runtime efficiency and have poor maintainability. The design goals for a cross layer feedback architecture are efficiency, rapid prototyping, minimum intrusion, portability and any-to-any layer communication. Existing approaches to cross layer feedback do not address all the design goals.

In the next chapter we present our cross layer feedback architecture – ECLAIR, which addresses the stated design goals.

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What's in a name? That which we call a rose
By any other name would smell as sweet
- William Shakespeare

Chapter 3

ECLAIR: An Efficient Cross Layer Architecture

3.1 Introduction

In Chapter 2 we presented a survey of existing mechanisms for cross layer feedback and discussed their merits and demerits. We also identified the design goals for a cross layer feedback architecture, namely: efficiency, minimum intrusion, rapid prototyping, portability and any-to-any layer communication.

In this chapter we present our cross layer feedback architecture – ECLAIR, which is based on the above design goals. Below, we present the scope of ECLAIR architecture specification.

3.1.1 Scope

We restrict the scope of this thesis to a discussion about the architectural aspects of cross layer feedback. In this chapter,

- we describe the functionality and interface of each component of ECLAIR
- we describe typical generic (operating system independent) APIs [1]

[1] Application Programming Interfaces

- we present API examples specific to Linux [99]

However, the following are beyond the scope of this thesis:

- an exhaustive list of APIs specific to an operating system
- issues intrinsic to cross layer feedback such as *dependency cycles* (or adaptation loops) and *conflicts* [41]. For example, a dependency cycle is formed if TCP reads information about the interface queue at the MAC layer to adapt TCP retransmissions, while the MAC layer reads TCP retransmission information to adapt MAC retransmissions. Another issue intrinsic to cross layer feedback is adaptation conflict. For example, a conflict would occur if two cross layer adaptations try to change physical layer transmit power at the same time.

In Chapter 4 we present implementation of a ECLAIR prototype on Linux [99], using Receiver Window Control [66] as an example. Next, we present the acronyms used in this chapter.

3.1.2 Acronyms

Table 3.1 lists the acronyms used in this chapter.

3.2 Background: Protocol Implementation Overview

Before presenting an overview of ECLAIR, we present an introduction to a protocol's implementation in an operating system. We use Linux [99] as an example. A protocol's implementation consists of protocol algorithms and data structures. A protocol's data structures have two major components – *control* data structures and *data* (or protocol data unit) data structures. The control data structures determine the behavior of a protocol. For example, control data structures are used for implementing the state machine of a protocol. Some examples of control data structures are: timers controlling behavior of MobileIP, retransmit timer in TCP, fragmentation threshold in 802.11 [33].

Example: TCP control data structures

We use TCP as an example to explain the concept of control data structures. In the examples below, the `linux` directory implies the directory where the Linux [101] source code is installed. In Linux (IPV4), TCP algorithms are implemented in the `linux/net/ipv4/tcp*.c` files. For example, TCP receive functions are implemented in `tcp_input.c`. TCP's protocol data structures are implemented in `linux/include/sock.h` and `linux/include/tcp.h` files. These data structures are accessed by the algorithms

implemented in the `tcp*.c` files. One of the important control data structures for TCP is `tcp_opt`. This is implemented in `linux/include/net/sock.h` files.

Acronym	**Description**
802.11	IEEE Standard for WLAN
ATL	Application Tuning Layer
GPRS	General Packet Radio Service
GSM	Global System for Mobile communications
IP	Internet Protocol
IPTL	IP Tuning Layer
MAC	Medium Access and Control layer
MTL	MAC Tuning Layer
NTL	Network Tuning Layer
OSS	Optimizing SubSystem
PHY	Physical layer
PO	Protocol Optimizer
PTL	PHY Tuning Layer
QoS	Quality of Service
RTS	Request to Send
CTS	Clear to Send
TCP	Transmission Control Protocol
TCPTL	TCP Tuning Layer
TL	Tuning Layer
TTL	Transport Tuning Layer
UDP	Universal Datagram Protocol
UDPTL	UDP Tuning Layer
UTL	User Tuning Layer
WLAN	Wireless Local Area Network

Table 3.1: Table of acronyms

Some of the fields in `tcp_opt` are *retransmission time out* `rto`, *smoothed round trip time* `srtt`, *maximal window to advertise* `window_clamp` and *slow start threshold* `snd_ssthresh`. These fields are read and written to at various points in the TCP code. The values in these and other fields determines TCP behavior as TCP code executes. For example, TCP retransmits packets when the retransmission timeout timer expires. The value in `tcp_opt.rto` is used for setting TCP's retransmission time out. The value of `tcp_opt.rto` is updated at various points the TCP code and is used to set the *retransmit timer*. The timer used for this is a *kernel timer* [13]. This kernel timer is *accessible* through the variable `tcp_rto.retransmit_timer`. TCP retransmission behavior can be changed by modifying this retransmit timer. Similarly, the values in the control data structures of various layers can be changed to modify the behavior the protocols.

Accessible control data structures

Accessible control data structures are the protocol's control data structures which can be accessed by kernel components. This accessibility is enabled during kernel compilation. For example, in Linux, the access to network variables is enabled in the file `linux/net/netsyms.c`, using the macro `EXPORT_SYMBOL`. `tcp_hashinfo` provides access to the TCP socket hash tables.

ECLAIR uses these accessible control data structures to manipulate protocol stack behavior. In the next section, we present an overview of ECLAIR.

3.3 ECLAIR Overview

3.3.1 Architectural Model

For the description of ECLAIR we use simple functional block diagrams. The blocks shown in the architecture are functional blocks. The actual implementation may be as separate modules or combined modules. We depict interfaces between the components by use of arrows and lines. We explain the notation as we use it. In Chapter 5, Section 5.3.1, we propose an notation which is useful for an overview of cross layer feedback implementation.

ECLAIR is not tied to any specific hardware. All components are primarily software components. However, we do not mandate an implementation in software only. The system developer may implement components in hardware, software or both.

The cross layer system designer may choose to introduce hardware or OS specific constructs to enhance efficiency. We describe an ECLAIR sub-architecture to enhance the efficiency of ECLAIR, in Chapter 6. The next section provides an overview of ECLAIR components.

3.3.2 Component Overview

In this section we provide an overview of our architecture – ECLAIR. ECLAIR's primary characteristics are: (1) it is outside the existing stack, that is, minimal modifications, if any, are required to the existing stack's code and (2) it is almost entirely in kernel-space i.e. most of the components of ECLAIR reside in the kernel and hence have access to certain kernel data structures (see accessible data structures in Section 3.2).

ECLAIR consists of an *Optimizing SubSystem* which contains the cross layer feedback algorithms and *Tuning Layers* which provide an interface to the existing protocol stack. Figure 3.1 shows an overview of ECLAIR.

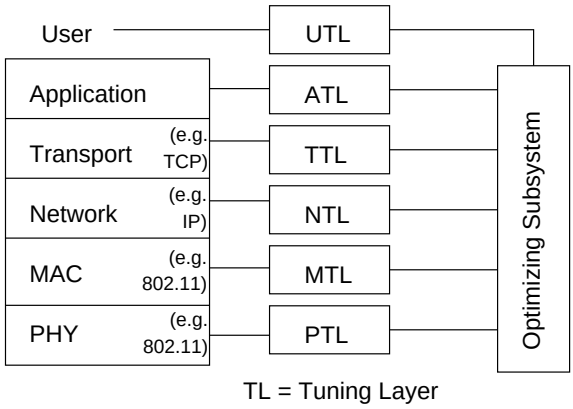

Figure 3.1: ECLAIR architecture

3.3.3 Tuning Layer

ECLAIR provides one *Tuning Layer* (TL) for each layer of the stack (Figure 3.1). The TLs do not interact with each other directly. A TL provides an interface to a protocol's control data structures (Section 3.2).

TLs are used by the Optimizing SubSystem (OSS). A TL monitors a protocol's control data structures for the current state of the protocol. The TL is aware of the implementation details (control data structures) of a protocol's data structures. It is used by the OSS to manipulate protocol behavior by effecting changes to the protocol's *accessible* control data structures.

The Tuning Layers for a typical protocol stack are: Physical Tuning Layer, MAC Tuning Layer, Network Tuning Layer, Transport Tuning Layer and Application Tuning Layer. ECLAIR also provides a *User Tuning Layer* for allowing user interaction with the protocol stack. Each TL contains appropriate components for a protocol within the layer. For example, MAC TL contains 802.11 TL for 802.11 [33] and GPRS TL for GPRS [48]. Similarly, Network TL contains IP and Mobile-IP TL; Transport TL contains TCPTL, UDPTL, etc; Application TL contains application specific TLs.

Each TL is subdivided into a generic and implementation specific sublayer. This is useful (we evaluate ECLAIR in Chapter 5), since the implementation of protocols is different across systems, even though they conform to the protocol standards. For example, the TCP data structure names are different in NetBSD [104] and Linux [99]. The OSS uses the generic API of TLs. The generic interface invokes the implementation specific API for a particular OS. Next, we present an overview of the Optimizing SubSystem.

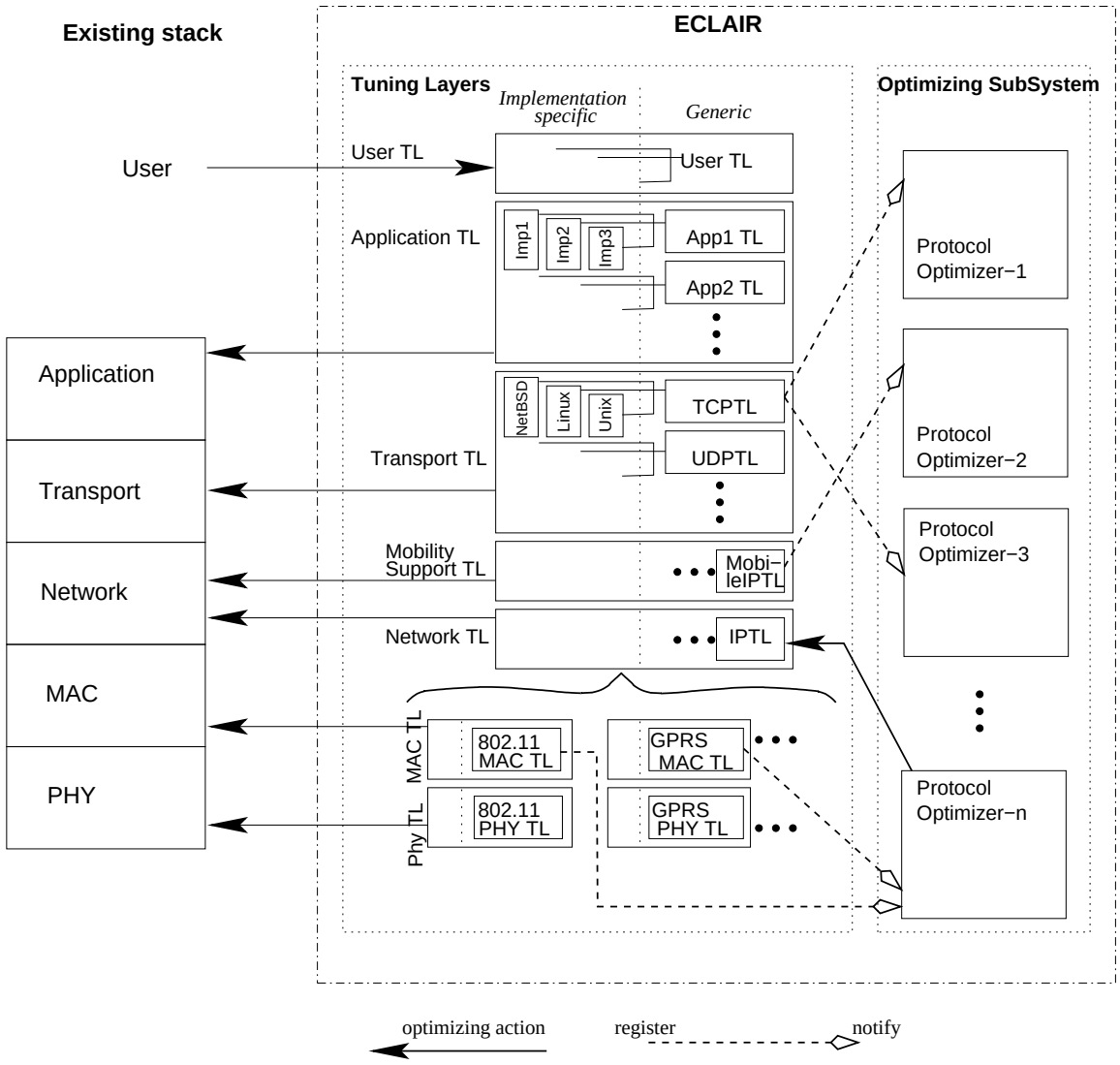

Figure 3.2: ECLAIR architecture details

3.3.4 Optimizing SubSystem

The OSS determines the cross layer optimizations. The OSS contains many protocol optimizers (POs). A PO contains the algorithms and data structures for a specific cross layer optimization. A PO registers with a TL for event information from a particular protocol layer. Figure 3.2 depicts this registration as a dashed line with hollow arrow head. The PO's algorithm determines the cross layer optimizing action. The PO invokes the appropriate TL's generic API for modifying the control data structure, and consequently the behavior, of the *target* protocol. Figure 3.2 depicts this optimizing action by a solid line with a solid arrow head. An ellipsis next to a TL (example, UDPTL) represents additional TLs at a layer. An ellipsis within the OSS represents additional POs. To illustrate the working of ECLAIR we present a few examples in the next section.

3.4 Cross Layer Feedback using ECLAIR: Examples

In this section we present three examples based on ECLAIR. The first two examples are about cross layer feedback to TCP (1) from the *user* and (2) from the network layer (Mobile-IP). The third example describes how ECLAIR supports seamless mobility.

3.4.1 User Feedback

Users can provide useful feedback to improve the performance of the stack or the *user experience*[64, 66]. For example, a user may want one file download to get more bandwidth than another.

Algorithm: One method of controlling the application's bandwidth share is through manipulation of the *receiver window* of its TCP connection [66]. The user assigns some priority number to each application. An application's priority number p is used to calculate its receiver window, $r = R \times p / \sum p$ [66], where R is the total available receive buffer. Details of this algorithm are presented in Section 4.1.1.

Implementation: The use of ECLAIR for the above PO (*Receiver Window Control PO* or *RWC PO*) is shown in Figure 3.3.

The explanation of the sequence shown in Figure 3.3 is as follows: **(1)** TCPTL gets *protocol block head* information at system start. **(2a),(2b)** PO registers for *user* events. User changes priorities for running applications. **(3)** Application and respective priority information is passed to the RWC PO. **(4a),(4b)** Current receiver window/buffer information is collected via TCPTL. This information is used to recalculate the new receiver window values for the various applications. It is assumed that the application can be identified by the sockets. **(5a),(5b)** The receiver window values are set for each application.

In the Figure 3.3, the fine dotted line from the TCP data structures `sock` and `tcp_opt` represent *pointers* to other data structures. The ellipsis next to `sock()` represents other `sock()` structures. The ellipsis within RWC PO represents the RWC cross layer algorithm.

3.4.2 Adapted TCP

TCP is known to perform poorly when there are disconnections since it misinterprets disconnections as network congestion and decreases its sending rate [58, 75, 85]. TCP performance can be improved through feedback from other layers.

Algorithm: Feedback from the network layer about disconnections can be used to adapt TCP behavior. A number of such improvements are proposed in [68]. One of the improvements suggested is: if disconnection occurs and if the *congestion window*(*cwnd*) is open, then cancel TCP retransmission timer and do not reduce the *cwnd*. On reconnection,

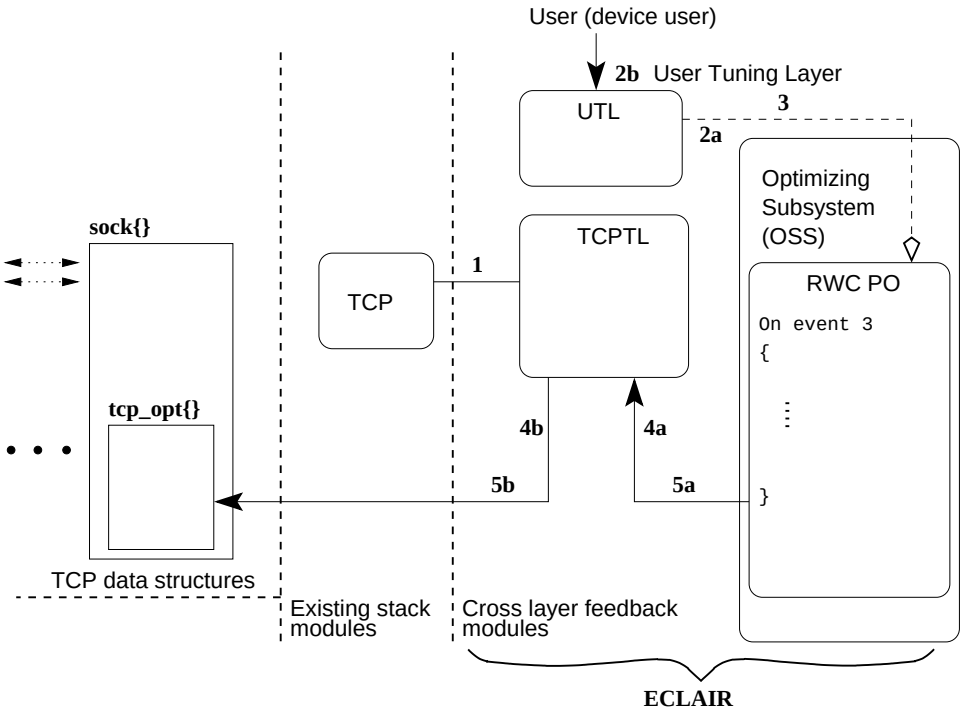

Figure 3.3: ECLAIR architecture: User feedback

use the earlier *cwnd* and set a new retransmission timer. This action results in improved TCP throughput since unnecessary reduction in *cwnd* is avoided.

Implementation: The use of ECLAIR for the above PO (*Adapted TCP PO* or *ATCP PO*) is shown in Figure 3.4. The explanation of the sequence shown in Figure 3.4 is as follows: **(1a),(1b)** The data structure location information is acquired by TLs at system startup. **(2a),(2b)**PO registers for disconnection(reconnection) event. MITL monitors the network status for disconnection(reconnection). **(3)** Disconnection(reconnection) occurs and ATCP PO is notified. **(4a),(4b)** Current state of TCP is queried via TCPTL and the action is determined (for example, changing the value of the TCP retransmission timer). **(5a),(5b)** The TCP retransmission timer is set to the new value determined in step 4.

In the Figure 3.4, the ellipsis and fine dotted line notation is same as that described in the previous RWC example. The looped arrow **(2b)** implies continual monitoring of *Network info*.

3.4.3 Seamless Mobility

Seamless mobility means the continuation of a session on a mobile device even as it roams across heterogeneous wireless networks [14]. The key requirement is that the session should continue uninterrupted. We discuss an example PO for seamless mobility between GPRS [48] and 802.11 [33] WLAN networks.

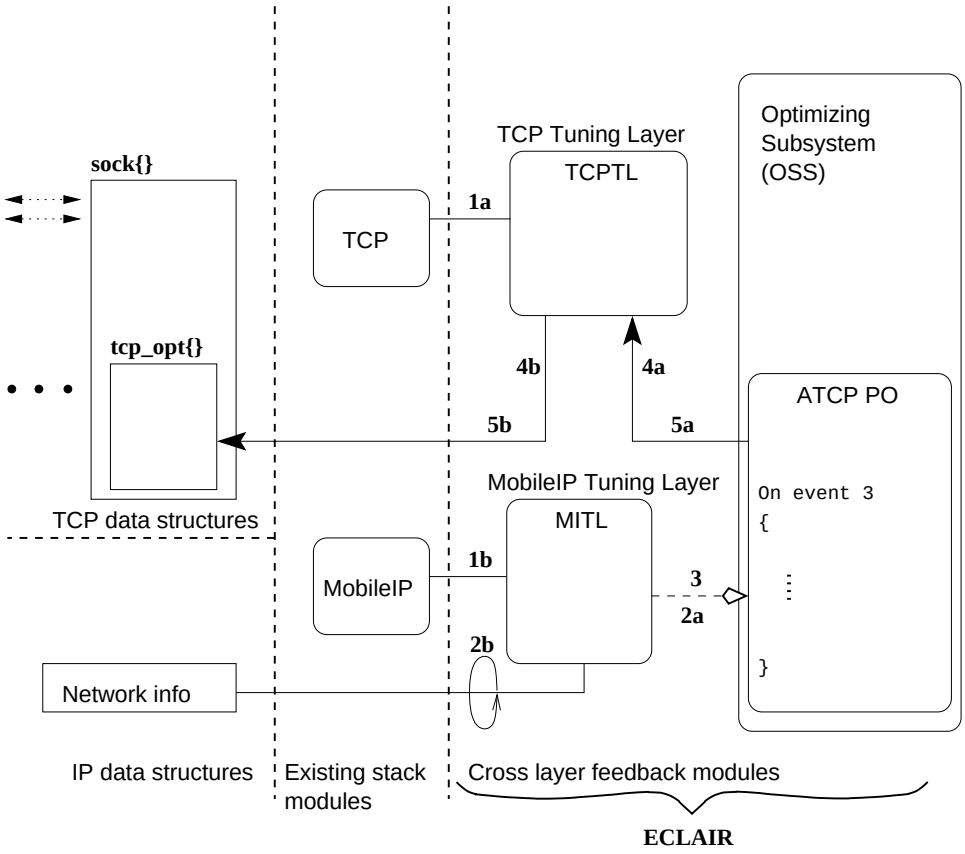

Figure 3.4: ECLAIR architecture: Adapted TCP

Algorithm: For achieving seamless mobility MAC layers of the GPRS and 802.11 interfaces are monitored for *vertical* handoffs. When the wireless network changes the corresponding wireless interface is made active in the IP layer.

Implementation: The use of ECLAIR for the above PO (*Seamless Mobility PO* or *SM PO*) is shown in figure 3.5. The explanation of the sequence shown in Figure 3.5 is as follows: **(1a),(1b)** The data structure location information is acquired by the TLs at system startup. **(2a),(2b)** PO registers for disconnection(reconnection) event. MAC TL monitors the network status for disconnection(reconnection). **(3)** Disconnection(reconnection) occurs and SM PO is notified. **(4a),(4b)** Current state of interface in IP is queried via IPTL and the action is determined (for example, changing the active interface). **(5a),(5b)** The active interface in the IP layer is set to the interface determined in step 4.

Note that, switching on an interface could be slow process, since it depends on the time taken for the interface to switch on and register on the network. Thus, seamless mobility may not be smooth in case one interface is switched off and then another is switched on. To ensure fast switchover to the new interface, the new interface could be switched on when the seamless mobility PO detects that the signal on the existing interface has turned weak. Till the existing interface is switched off, packets could be sent on both

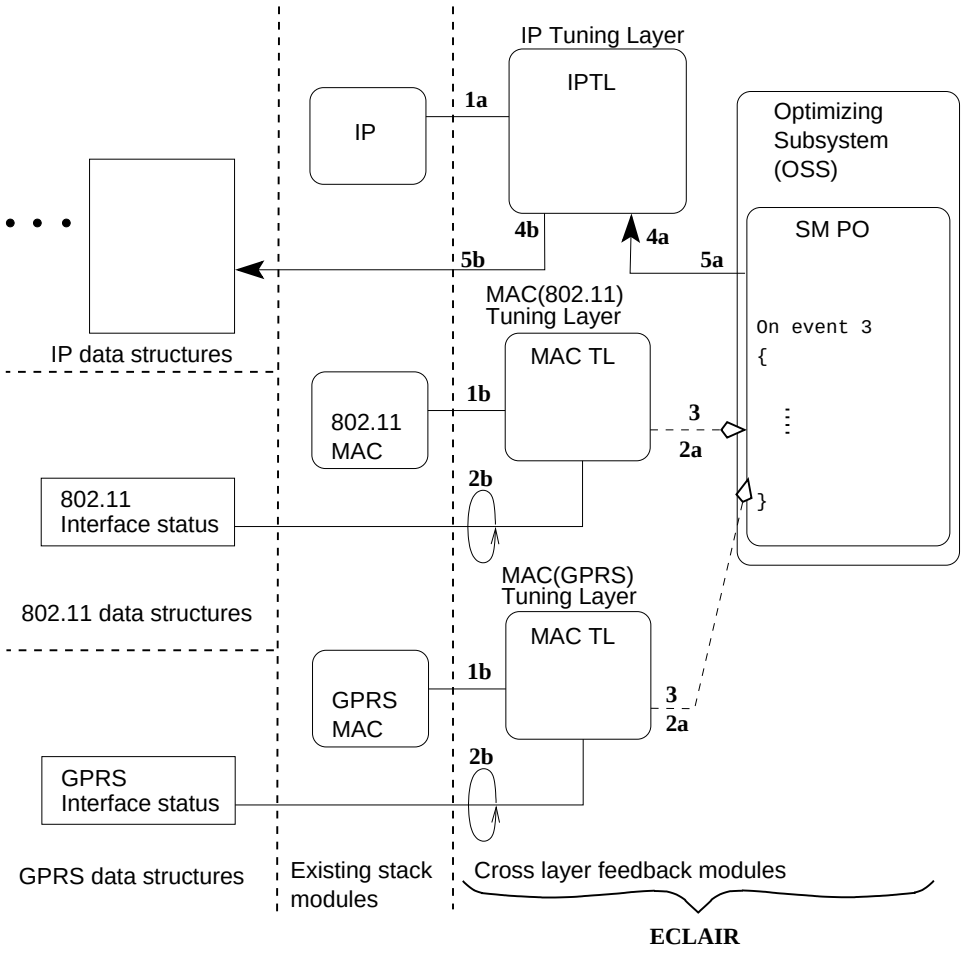

Figure 3.5: ECLAIR architecture: Seamless mobility

the interfaces. For determing the exact instance when packets should be sent on multiple interfaces, and when the handover should be completed, extensions to Stream Control Transport Protocol (SCTP) [72], such as the Multi-path Transmission Algorithm [40] could be used.

In the Figure 3.5, the fine dotted line and ellipsis notation are same as that described for the RWC PO above. The looped arrow **(2b)** implies continual monitoring of 802.11 and GPRS interfaces.

Above, we presented an overview of ECLAIR and some examples of cross layer design based on ECLAIR. Next, we present architectural details of ECLAIR components – Tuning Layers and Protocol Optimizers. We also discuss the working of these components and present their APIs.

3.5 ECLAIR Details: Tuning Layer Specification

3.5.1 Introduction

A Tuning Layer provides an interface to the control data structures of a layer in the protocol stack. Each TL contains appropriate components for each protocol in a layer. A TL reads from/writes to the *accessible* (Section 3.2) control data structures of a protocol. A TL is implemented in user or kernel-space depending on whether the layer to be tuned is in the user or kernel-space. Next, we provide the details of TL interaction and interfaces with other components of ECLAIR and the operating system.

3.5.2 Software Component View

Figure 3.6 shows the software component view of the Tuning Layers. The figure shows an overview of the interaction of TLs with the other components of ECLAIR.

A TL has separate components for the each protocol in a layer, for example, MAC-TL has 802.11-TL. Application and User Tuning Layers are in *user-space* while the rest of the Tuning Layers are in *kernel-space*. We discuss the advantages of this approach in Chapter 5.

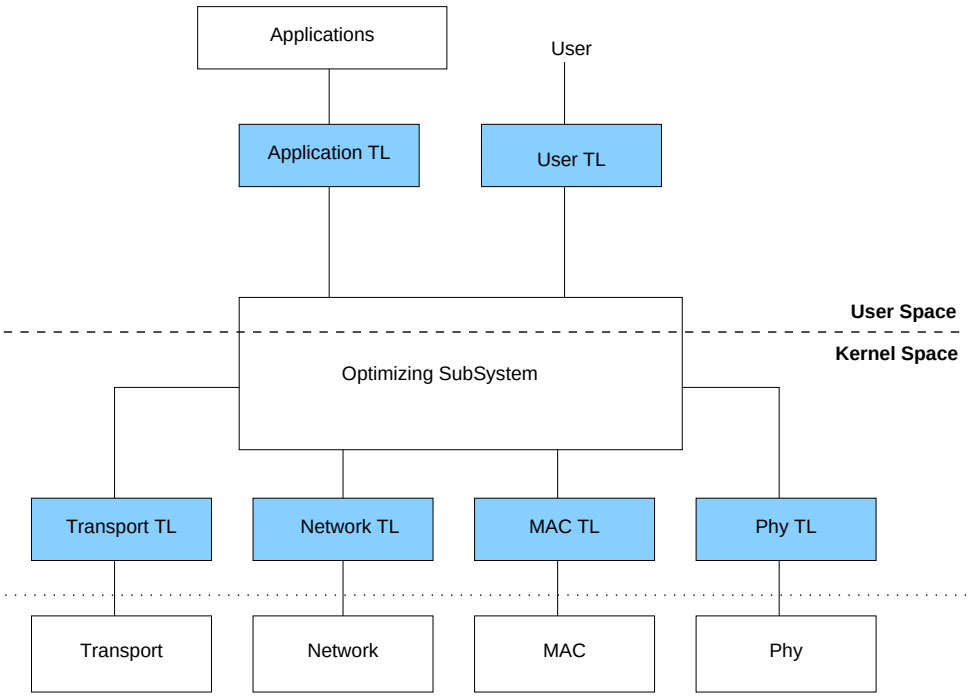

Figure 3.6: ECLAIR Tuning Layers - Software component view

3.5.3 Tuning Layer Interface with other Components

Figure 3.7 depicts the interfaces of a TL with a PO. The TL provides the following APIs:

- *register* to enable POs to specify *events* which are to be monitored
- *unregister* to enable a PO to unregister
- *get* to enable a PO to read a control data structure of a protocol
- *set* to enable a PO to update the value of a control data structure of a protocol

To deliver events to a registered PO, a TL uses the PO's callback function or a queue. We provide some implementation guidelines in Chapter 7.

For *get* or *set*, the PO does not specify the data structure, it only specifies the action using the TL API. The TL ensures that the appropriate data structure is located and read or updated. For protocols having multiple flows, the API allows update to a specific flow or across all flows (for cross layer feedback classification see Chapter 1, Section 2.5.1). For example, an update may be applied to all TCP connections, while some update may be applied to a single TCP session.

3.5.4 Tuning Layer API Sub-Layer

As stated in Section 2.5, portability is an essential design goal for cross layer architecture. For the purpose of portability a TL is subdivided into a *generic tuning sublayer* and an *implementation dependent access sublayer*. This separation is useful since the implementation of protocol stacks is different (for example, different data structure names may be used) across systems, even though all of them may conform to the layered architecture and protocol standards.

The generic tuning sublayer provides an implementation independent interface to the PO for a specific protocol. Implementation independent means that the generic tuning sublayer API is common for all implementations of a protocol, irrespective of the underlying operating system. This generic API is used by the protocol optimizers (POs) for effecting changes in a protocol's behavior. The generic tuning sublayer in turn invokes appropriate implementation dependent sublayer API, for operating system specific actions.

The implementation dependent sublayer provides implementation specific interfaces for a protocol. For example, separate interfaces are provided for each implementation of TCP in Unix [106], NetBSD [104] and Linux [99].

Below we present an example of generic and implementation specific layers for Receiver Window Control [66]. For tuning TCP receiver window, the generic tuning sublayer API in TCPTL, is

```
set_recv_win ( source_address, source_port,
               destination_ipaddress, destination_port,
               receiver_window_value);
```

The corresponding implementation specific API in TCPTL, for Linux is

```
linux_set_recv_win ( source_address, source_port,
                     destination_ipaddress, destination_port,
                     receiver_window_value);
```

The above API is used to set `tcp_opt.window_clamp` to `receiver_window_value` in Linux. We describe TCP Receiver Window Control implementation using ECLAIR in Chapter 4.

The generic APIs would be bound to the appropriate implementation specific APIs according to the compile time configuration. Next, we present the working of a Tuning Layer.

3.5.5 Tuning Layer – Theory of Operation

Dependencies:
A TL needs to access the data structures of a protocol and hence the protocol data structures should be *accessible* (Section 3.2). On system start-up the various protocol data structures of the stack are instantiated and initialized. A TL for a protocol is initialized after this, to enable it to access the protocol's control data structures.
Initialization:
Initialization involves setting up the data structures of the TL. A TL *exports* (see reference [13] and Section 3.2) some of its functions and data structures for use by the OSS.
PO registration:
Figure 3.7 shows the interface between a TL and PO. The TL provides a function for the PO to *register* for information about a specific *event*. An event is the change in the value of a data structure within a protocol. The PO specifies the event(s) of interest. The PO may also specify a callback function for event notification. Multiple POs may register for the same event. Also, a single PO may register for multiple events.

For protocols with multiple flows, a PO may specify a particular flow, within the protocol, that needs to be monitored. For example, TCP may have multiple simultaneous flows. In absence of flow specification, an event implies the event occurring in ANY of the flows within the protocol. The TL also provides a function for the PO to *unregister* from an event notification.
Event monitoring:
Using the registration information provided by the PO, the TL determines the protocol data structure to be monitored. The TL monitors a protocol for events by monitoring

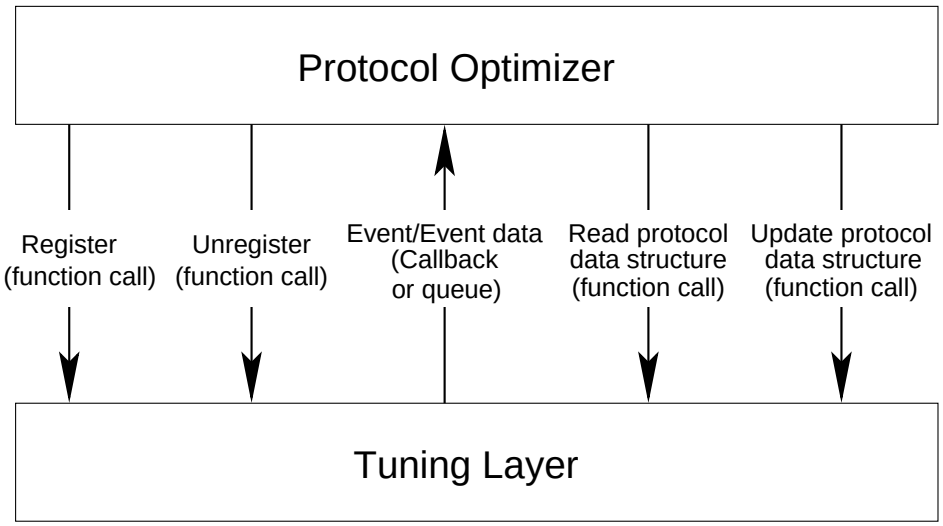

Figure 3.7: ECLAIR Tuning Layers - Interfaces with PO

specific control data structures of the protocol. The frequency of monitoring is specified by the PO. The TL monitors an event with the maximum specified frequency, from those specified by the various POs interested in the event. Some of the interesting events at various layers are:

- *User:* Change in application priorities
- *Application:* Change in applications *quality of service* requirements
- *Transport(e.g. TCP):* Retransmission timeout, change in *round trip time*
- *Network(e.g. Mobile-IP):* Handover initiation or completion
- *Medium Access Layer:* Collision occurrence
- *Physical:* Change in signal strength

Event notification:
When an event occurs, the TL *notifies* all the registered POs. The notification to a PO is at the monitoring frequency specified by the PO while registering. The event notification to the POs is in no particular order. This notification is either *synchronous* or *asynchronous*. For synchronous notification, the callback function registered by the PO is used. For asynchronous notification an event notification queue is used.

On receipt of event information from a TL, the PO determines appropriate cross layer action and uses the TL API to effect a change in the behavior of the target layer. The PO invokes a generic API which in turn invokes the appropriate implementation specific API.

Changing protocol behavior:
The implementation specific function updates the appropriate data structure with the

values provided by the PO to change the protocol behavior. The implementation specific function implements efficient algorithms to locate the correct data structure within a protocol.

Unload, cleanup:

A TL is unloaded when a *fatal* error occurs, during TL processing or on system shutdown. For example, a *pointer* to some memory in the TL program, expected to have some value, may be null. Unload means disabling the TL till the system is rebooted. When the TL is unloaded:

- the POs registered with the TL are unregistered
- all the data structures allocated by the TL are de-allocated
- any data structure update in progress is aborted
- the TL logs the reason for unload

During system shutdown, the TL is unloaded before the protocol stack shutdown.

Error Handling:

The TL reports success or error message to the caller for each function call.

As stated earlier, certain issues which are intrinsic to cross layer feedback, for example, *dependency cycles* and *feedback conflict* [41] are not handled by any specific component within ECLAIR. Defining such a component is beyond the scope of this thesis. However, ECLAIR TLs and POs can be used to handle such cross layer feedback problems (see Chapter 7).

Logging / debugging:

This is primarily provided for debugging the cross layer system. In case debugging is *on*, the TLs log to a file each PO's call and the list of parameters with their values and the final result (return code). During unload a TL logs the reason for unload to a log file, even if debugging is *off*.

Above we described the working of a TL. In the following sections we describe the APIs provided by the various TLs. This specifies the minimum APIs that should be provided by a TL. However, the cross layer designer may choose to add or delete APIs as required. For Transport, Network, MAC and Phy layers, we present the API for one example protocol in the layer. For example, we provide the APIs of TCPTL in Transport TL.

3.5.6 User TL

Figure 3.8 shows the interface between User TL and other components. User TL provides an interface to the *device user* for interacting with the protocol stack. The device user

can be a person using the mobile device or an external entity such as a component of a distributed algorithm. UTL can be used to pass user requirements to the protocol stack. These requirements are mapped to a protocol specific parameter within ECLAIR (for example, see Receiver Window Control – RWC [66], in Section 4.1). Further, UTL can be used to *get* or *set* the value of a specific parameter within the stack.

UTL interaction with PO:

Figure 3.8 shows UTL interface with a PO. A separate PO is created that handles UTL interaction. This PO registers functions with the operating system for interaction with UTL. Since the UTL is in user-space its interaction with the PO in kernel-space is through operating system mechanisms. For example, in Linux, this PO can be a *character driver* and would receive `ioctl()` commands for a special file created for interaction with user-space (see Chapter 7). We use this technique for RWC in Chapter 4. We highlight the benefit of ECLAIR UTL as compared to a standard system call in Chapter 5. Next, we present the UTL APIs.

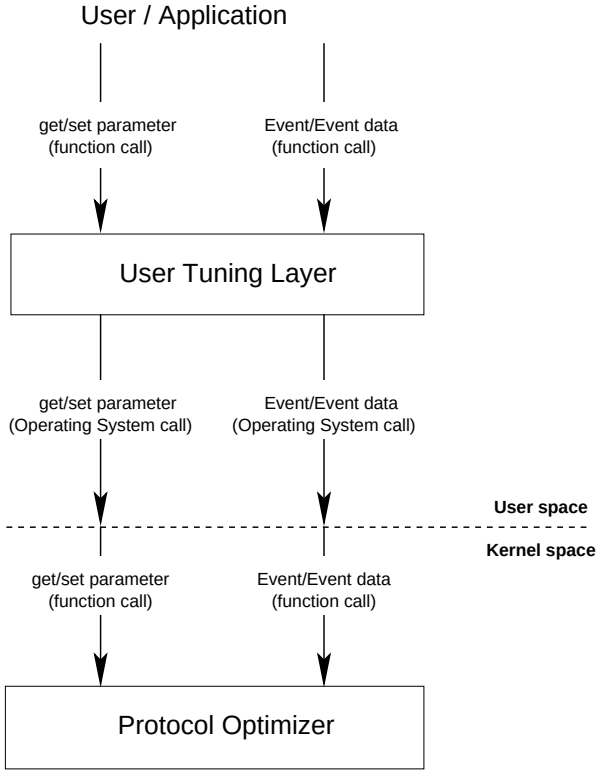

Figure 3.8: User Tuning Layer Interfaces

- *Name:* get_stack_parameter()

Input Parameters: Identifier of parameter (for example, TX_POWER for transmit power),
Connection identifier (if applicable to a single session),
VAR_RETURN: Address of variable for returning data

Returns:	Value of queried parameter in VAR_RETURN (Number | String), Return Code (Number)
Description:	Gets the value of specified stack parameter

•*Name:*	set_stack_parameter()
Input Parameters:	Identifier of parameter (for example, TX_POWER for transmit power), Connection identifier (if setting applicable to a single session), Value of parameter (Number | String)
Returns:	Return Code (Number)
Description:	Sets the specified stack parameter to the given value.

•*Name:*	set_application_priority()
Input Parameters:	Connection identifier(s) (for example, socket details – source address & port, destination address & port) Application priority (or priorities) (Number)
Returns:	Return Code (Number)
Description:	Sets priority for an application. Sets relative priority if multiple applications specified.

•*Name:*	handoff()
Input Parameters:	New interface (String | Number), Time delay (Number)
Returns:	Return Code (Number)
Description:	Initiates handoff to the specified interface after the specified time delay

•*Name:*	crosslayer_shutdown()
Input Parameters:	–
Returns:	Return Code (Number)
Description:	Sends *shutdown* event to user PO

Before presenting the APIs for the rest of the layers, we present two APIs which are common to all the remaining TLs.

3.5.7 Common TL APIs

The following APIs are common to the TLs of Application, Transport, Network, MAC and Phy.

•*Name:*	register()
Input Parameters:	[Call back function], Event name (String)
Returns:	Return Code (Number)
Description:	PO registers for *event* of interest. A callback function is registered for each event. If no callback function is specified, TL returns a pointer to the event notification queue

•*Name:*	unregister()
Input Parameters:	Event name (String)
Returns:	Return Code (Number)
Description:	Unregister PO for specified *event*

3.5.8 Application TL

Application Tuning Layer allows applications to interact with the protocol stack. An application can specify its QoS requirements using the Application TL. The ATL's purpose is to monitor application events and pass the event information to POs within the stack. Further, the ATL provides APIs to tune applications.

ATL interaction with PO:

Figure 3.9 shows ATL interaction with a PO. Since the ATL is in user-space its interaction with a PO in kernel-space is through operating system mechanisms. To receive an update instruction from a PO in kernel-space, the application PO registers with a PO in kernel-space. This kernel PO is created specifically for application interactions with the kernel-space. This PO in turn interacts with other POs in the OSS. It serves as an agent for the applications.

An application can register a call back function for specific events. Alternatively, a PO can be created externally that registers on behalf of an application. This PO tunes the application when an event occurs in the stack. Figure 3.9 shows the application TL's interface with a PO and an application. Some Application TL APIs are listed below.

•*Name:*	app_qos_requirements()
Input Parameters:	QoS parameters – Bandwidth (Number), Delay (Number), Losses (Number)
Returns:	Return Code (Number)

Description:	Pass application QoS (Quality of Service) requirements, that is, bandwidth, delay, losses acceptable, to the cross layer POs.

•*Name:*	get_connection_cost()
Input Parameters:	Interface (String | Number) | Void
Returns:	Cost per minute of connection (Number) | Return Code (Number)
Description:	Fetches cost per minute of specified interface (current interface if input parameter is void)

Applications or POs can use the APIs provided by UTL for accessing other parameters of the stack. Next, we present the APIs for TCPTL as an example for Transport TL.

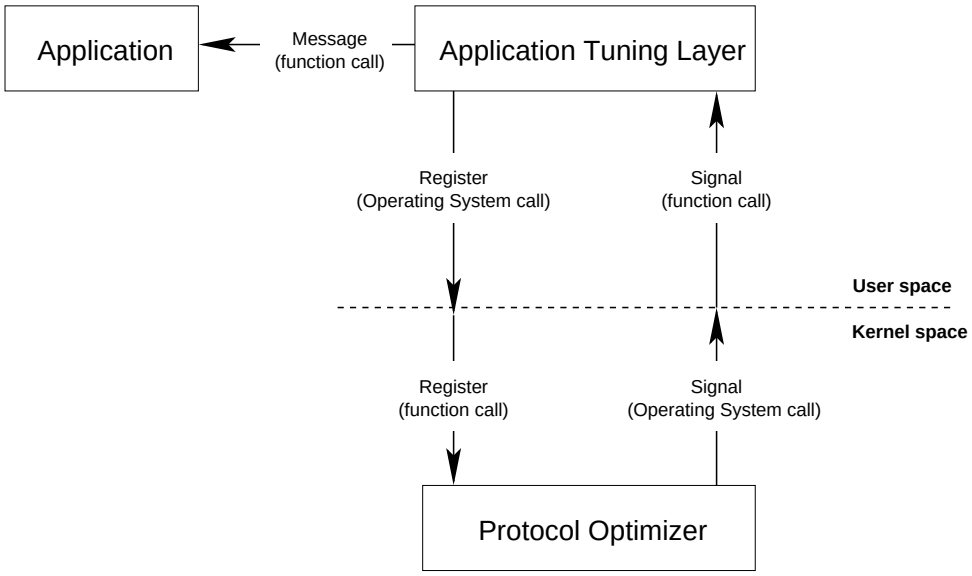

Figure 3.9: Application Tuning Layer Interfaces

3.5.9 Transport TL

Transport TL provides components for tuning the transport layer protocols. We present some example APIs for TCP TL. TCP TL allows query and update of various control data structures within TCP. The APIs can be used to query or update the values of a specific TCP flow or all TCP flows. Additional APIs are listed in the Appendix, Section I-1.

For all the APIs, TL implementation ensures *correct* and *fast* location of the appropriate connection. The TL implements appropriate algorithms for fast location. In the following, *socket identifier* means the 4-tuple *source address* & *port*, *destination address* & *port*.

TCP TL APIs:

- *Name:* get_receiver_window()
  Input Parameters: socket identifier
  Returns: Value of receiver window (Number) | Return Code (Number)
  Description: Locates the socket and returns receiver window value

- *Name:* set_receiver_window()
  Input Parameters: Socket identifier, value of receiver window (Number)
  Returns: Return Code (Number)
  Description: Locates the socket and updates the value of receiver window

- *Name:* get_tcp_state()
  Input Parameters: socket identifier
  Returns: State of TCP flow (Number) | Return Code (Number)
  Description: Locates the socket and returns the state of TCP flow (from list of standard TCP states)

- *Name:* set_tcp_state()
  Input Parameters: Socket identifier, TCP state (Number)
  Returns: Return Code (Number)
  Description: Locates socket and updates TCP state

Next, we present the APIs for IPTL and Mobile-IP TL as examples for Network TL.

3.5.10 Network TL

Network TL provides components for network layer protocols. We present some example APIs for IP.

IP TL

- *Name:* get_active_interface()
  Input Parameters: [Socket identifier]
  Returns: Active interface (String) | Return Code (Number)
  Description: Returns the current active interface. Returns active interface for a flow if socket specified

- *Name:* set_active_interface()
  Input Parameters: New interface (String)
  Returns: Return Code (Number)
  Description: Changes the current active interface

•*Name:*	get_frag_assy_timer()
Input Parameters:	–
Returns:	Current fragment reassembly timer (Number) | Return Code (Number)
Description:	Returns the value of fragmentation reassembly timer

•*Name:*	set_frag_assy_timer()
Input Parameters:	Timer value (Number)
Returns:	Return Code (Number)
Description:	Updates the value of fragmentation reassembly timer

Mobile-IP TL The following APIs have been defined based on the study of Mobile-IP RFC [59] and the code of Dynamics Mobile-IP implementation [97]. Additional APIs are listed in the Appendix, Section I-2.

•*Name:*	get_registration_lifetime()
Input Parameters:	–
Returns:	Duration (number) | Return Code (Number)
Description:	Returns the registration lifetime

•*Name:*	set_registration_lifetime()
Input Parameters:	Duration (number)
Returns:	Return Code (Number)
Description:	Updates the registration lifetime

•*Name:*	get_solicitation_rate()
Input Parameters:	–
Returns:	Rate (number) | Return Code (Number)
Description:	Returns the solicitation rate

•*Name:*	set_solicitation_rate()
Input Parameters:	Rate (number)
Returns:	Return Code (Number)
Description:	Updates the solicitation rate

Next, we present the APIs for 802.11-TL as an example for MACTL.

3.5.11 MAC TL

MAC TL provides components for tuning the transport layer protocols. We present some example APIs for 802.11-MAC-TL. Additional APIs are listed in the Appendix, Section I-3. Information about 802.11 is available in reference [33].

802.11 MAC TL

- *Name:* get_contention_window()
  Input Parameters: –
  Returns: Current contention window (Number) | Return Code (Number)
  Description: Returns current contention window value

- *Name:* set_contention_window()
  Input Parameters: Contention Window (Number)
  Returns: Return Code (Number)
  Description: Sets contention window to specified value

- *Name:* get_rts_cts_threshold()
  Input Parameters: –
  Returns: Current RTS/CTS threshold (Number) | Return Code (Number)
  Description: Returns current RTS/CTS threshold

- *Name:* set_rts_cts_threshold()
  Input Parameters: RTS/CTS threshold (Number)
  Returns: Return Code (Number)
  Description: Sets RTS/CTS threshold to specified value

3.5.12 Phy TL

MAC TL provides components for tuning the transport layer protocols. We present some example APIs for 802.11-Phy-TL. Additional APIs are listed in the Appendix, Section I-4.

802.11 Phy TL

- *Name:* get_transmit_rate()
  Input Parameters: –
  Returns: Current transmit rate | Return Code (Number)
  Description: Returns the current transmit rate of the active interface

•*Name:*	set_transmit_rate()
Input Parameters:	Transmit rate (Number)
Returns:	Return Code (Number)
Description:	Sets the transmit rate of the active interface

•*Name:*	get_transmit_power()
Input Parameters:	–
Returns:	Current transmit power () | Return Code (Number)
Description:	Returns the current transmit power of the active interface

•*Name:*	set_transmit_power()
Input Parameters:	Transmit Power (Number)
Returns:	Return Code (Number)
Description:	Set the transmit power of the active interface

In this section we described the details about TLs. ECLAIR does not require that all the TLs be implemented in a system. The cross layer designer can choose to implement only the required TLs for a system. In the next section we present details about the Optimizing SubSystem.

3.6 Optimizing SubSystem Specification

3.6.1 Introduction

The Optimizing SubSystem (OSS) contains cross layer feedback algorithms. It consists of multiple Protocol Optimizers (POs). Each PO contains an algorithm for a cross layer optimization. For example, a PO would contain the algorithm for modifying the transmit power based on current wireless environment.

3.6.2 Software Component View

Figure 3.10 shows the software component view of the Optimizing SubSystem (OSS) and the components with which it interacts.

A PO uses the APIs provided by the TLs to monitor the protocols for events and modify the protocol behavior. A PO may interact with one or more POs. Further, POs may interact with each other across the user-kernel boundary.

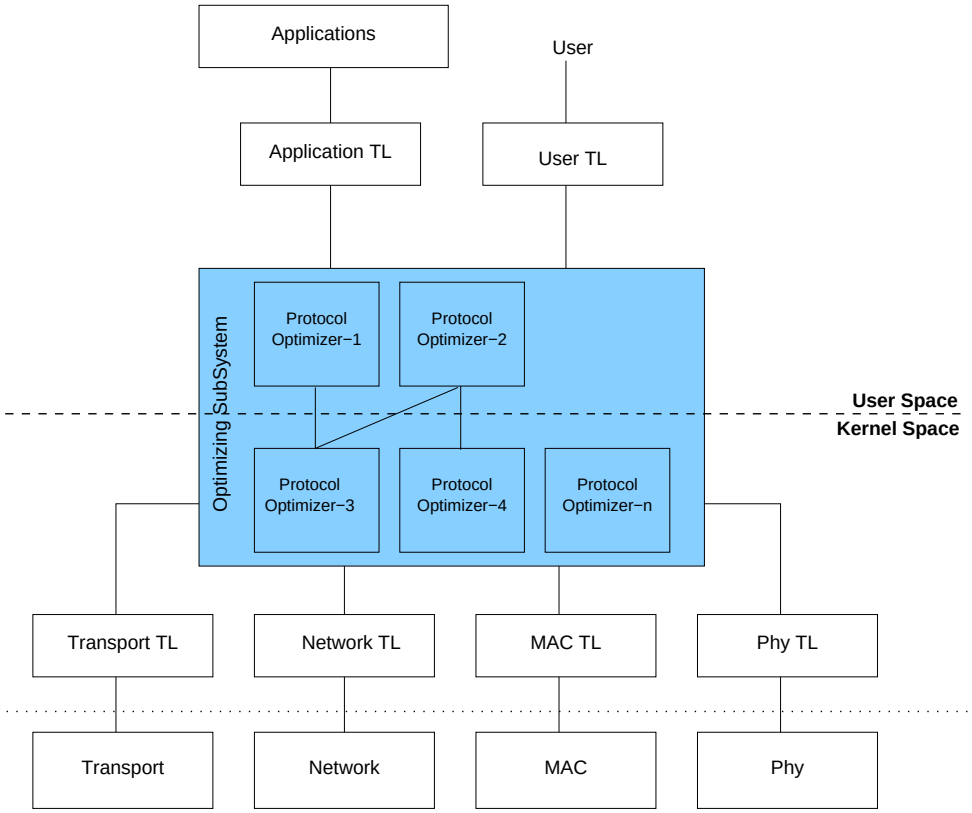

Figure 3.10: ECLAIR Optimizing SubSystem - Software component view

3.6.3 Optimizing SubSystem – Theory of Operation

Dependencies:
A PO is dependent on the TL and operating system APIs.

Initialization:
POs are initialized by the operating system. Since POs are dependent on TL APIs they are initialized after initialization of the protocol stack and TLs. On initialization, a PO registers for one or more events with the TL and waits for event notification from the TL (see Section 3.5).

Event notification:
The *notification* to PO could be synchronous or asynchronous. The PO provides a callback function to the TL for synchronous notification. For asynchronous notification the TL sends a *message* to the PO, in a message queue. The PO implements appropriate handler to receive and process the message.

The event notification contains an event identifier and value of the protocol data structure that caused the event.

Cross Layer algorithm:
Based on the cross layer event notification, appropriate cross layer algorithm is executed within the event handler in the PO.

The cross layer algorithm determines the layers that need to be adapted. Appropriate TL API is invoked to read the control data structures of the protocols that are to be adapted. The algorithm determines the new values for these control data structures. Appropriate TL API is invoked to update the control data structures with the new values so as to change the protocol behavior.

Using TL API:

The PO invokes the generic API of the target protocol's TL for reading or updating the target protocol's data structures. The generic API in turn invokes the implementation specific API. This implementation specific function call *locates* the appropriate data structure and reads and returns or updates the requisite protocol data structure.

For protocols with multiple flows, a PO may specify update to a specific flow, within the protocol. An update specified without a flow specification, implies an update to all the flows in the protocol.

Event processing:

The PO accepts and processes one event at a time. In case of asynchronous notification while an event is being processed, the other events received are queued.

Error handling:

In case of error returned by the TL, if *debug* mode is on, the PO logs the error number and the API invoked to the error log. In case *fatal* error is returned by the TL, the PO unregisters from all TLs. The PO remains unregistered till the PO is reinitialized.

Unload, cleanup:

A PO is unloaded when a *fatal* error occurs or on system shutdown. Unload means that the PO unregisters from all TLs and remains in that state till the system is rebooted. When a PO is unloaded, it:

- unregisters from all the TLs
- deallocates all its data structures
- aborts any procedure in progress
- logs the reason for unload

Disabling Cross Layer:

In case of a cross layer *shutdown* event from the user, the PO *unloads*. The *shutdown* event is generated by the user. The user PO registers with all the TLs at the time of OSS initialization. The user PO sends this event to all the TLs. The TLs in turn send this event to all the POs registered for *any* event. Subsequent to delivering the event to the POs, the TLs also unload. The cross layer system can be enabled again by rebooting.

Above we described the working of a PO. Next, we specify the functions that a PO must implement.

3.6.4 Procedures within PO

A PO implements the following procedures:

- *Cross layer feedback procedure:* This procedure contains the algorithm that determines adaptation of protocols. Its execution is triggered whenever an event is delivered to the PO.

- *Event handler:* is invoked when an event is delivered to the PO. It is called by the TL for delivering events to the PO, when registered as a callback function. The event handler invokes the appropriate cross layer adaptation procedure. A single event handler may handle multiple events.

- *Register procedure:* registers the event handler for each event, with the TL.

- *Unregister procedure:* unregisters the PO from the TL, for a particular event. The function determines the event for which the PO should unregister. This procedure is called from the *error handler* (see below).

- *Log procedure:* logs the TL API invoked and the error returned by the TL API. This procedure is invoked only if *debug* is enabled on the system.

- *Error handler:* is invoked when the TL API returns an error. In case of *fatal* errors, the error handler invokes the unregister function of the PO. In case debug is enabled, the error handler also invokes the log procedure.

In the sections above, we presented the working of ECLAIR and the architectural specifications for the components of ECLAIR. In the next section, we summarize the salient features of ECLAIR.

3.7 ECLAIR Salient Features

The salient features of ECLAIR are as follows:

- *User Tuning Layer*: Besides the layer specific TLs, ECLAIR also provides a *User Tuning Layer* (UTL). UTL allows a device user or an external entity, for example, a distributed algorithm or a base station, to tune the device behavior.

- *Event Notification*: TLs provide APIs which are used by the POs to register for interesting events at a layer. For example, TCP can register for handover completion event at the Mobile-IP layer.

- *Cross layer shutdown*: The POs and TLs are architected in such a way that in case of severe errors, the problematic PO will not carry out any further adaptations. Further, the user can disable the entire cross layer adaptation system, during run-time.

- *Support for seamless mobility*: ECLAIR can be used to enable seamless mobility [14] on the mobile devices. ECLAIR provides TLs for multiple protocols within a layer. A PO can be created that monitors and controls multiple wireless interfaces. This PO can adapt protocols as the device moves across heterogeneous networks and thus enable seamless mobility across these networks.

3.8 Summary

In this chapter we presented our cross layer feedback architecture – ECLAIR. We also illustrated the working of ECLAIR using some example POs. We presented the working, internal details and architectural specification of ECLAIR components, that is, Tuning Layers (TLs) and Optimizing Sub-System (OSS).

In the next chapter we describe an implementation (Receiver Window Control) using ECLAIR and validate it through experiments over Ethernet and Wireless LAN.

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Action is eloquence
- William Shakespeare

Chapter 4

ECLAIR Validation

In the earlier chapters we presented the motivation for cross layer feedback, the need for a cross layer feedback architecture, and presented our architecture – ECLAIR. In this chapter we validate ECLAIR. We use Receiver Window Control (RWC) [69, 54, 66] as a running example for explaining ECLAIR implementation and validation. In the next chapter we also use this implementation for a quantitative comparison of ECLAIR RWC performance with a user space implementation of RWC [54], and architectures proposing modification to the protocol stack. Before presenting the implementation details, we present an overview of RWC below.

4.1 Receiver Window Control

Users can provide useful feedback to improve the performance of the stack or the *user experience* [64, 66]. For example, a user may want a file download to complete faster than another simultaneous download on the device. One method of controlling an application's (which uses TCP) bandwidth share, on a *receiving* device, is through manipulation of the *receiver window* of its TCP connection. This approach is called *Receiver Window Control* [54, 66].

TCP uses congestion and flow control mechanisms to avoid swamping the network or the receiver [52, 61, 70]. The receiver reflects its receive buffer status in the *advertised window* field in the acknowledgments to the sender. When the sender is not congestion window limited, the receiver can control the transmission rate of the sender through the advertised window.

We note that throughput for a TCP connection is decided by the receiver window setting and the corresponding bandwidth-delay product [70]. In case of multiple flows, each having a different bandwidth-delay product, each of the flows will have a different optimum receiver window or advertised window(`awnd`). This property of `awnd`'s relation to the bandwidth-delay product can be exploited to *intentionally* make some of the TCP sessions get lower throughput, and thus dynamically control the application throughput. We call this approach *Receiver Window Control*(RWC). This assumes that total *actual* receiver buffer space is large enough to allow manipulation(increase or decrease) of the `awnd` *values* for the different sessions.

The current TCP implementations have fixed receive buffer sizes for all applications. Application level APIs are available, that allow an application to set its receiver buffer at the start of a connection [78]. However, once set it cannot be modified to reflect changes in application priorities.

The intuitive benefit of RWC can be seen from the following example: A user is running multiple downloads on a wireless device. The user increases the priority of one of the downloads. Through RWC, this higher priority is mapped to an increased `awnd` for the higher priority download . On the other hand, the `awnd` of the lower priority download is decreased. This would increase the throughput of the higher priority download. This control is dynamic and is invoked whenever the user changes application priorities. We now present the RWC algorithm [66].

4.1.1 RWC Algorithm

Let, n be the number of applications.
B = Bandwidth available to MH on the bottleneck link. B is shared among the n applications running on the MH. B is assumed to be constant.
$R = rtt$ for all the applications on the MH and is assumed to be constant.

The RWC algorithm is presented in Figure 4.1. The application priority number x_i is used for relative ordering of the applications and actual numbers have no significance. The ratio of the priority numbers is used in the algorithm.

We explain the RWC algorithm through an example. Consider three applications. Let, $A = 30$, $x_1 = 1$, $x_2 = 1$, $x_3 = 1$. Thus (from Figure 4.1) initially $awnd_1 = 10, awnd_2 = 10, awnd_3 = 10$. After user feedback, let $x_1 = 2$ (x_1, x_2 are not changed i.e. $x_2 = 1$ and $x_3 = 1$). Now, from Figure 4.1, $awnd_1 = round(\frac{2}{4} * 30) = 15$ $awnd_2 = round(\frac{1}{4} * 30) = 8$, $awnd_3 = 30 - (15 + 8) = 7$. Thus, it can be seen that RWC increases `awnd` for higher priority applications and decreases `awnd` for lower priority applications.

As the next step for validating ECLAIR we conducted some simulations of RWC using ns-2 [57]. These simulations help us determine the benchmarks for RWC using ECLAIR.

Events
UserFeedback: User changes priority of applications
Initialization
n = `number of applications`
B = `available bandwidth` // constant
R = `rtt` // constant
$A = B \times R$
$awnd_i$ = `default advertised window` // initially all equal
$x_i = 1$ // application priority; initially all equal
Function Calls
ReceiverWindowControl()
$cum\_awnd = 0$;
// User changes priority of applications; x_i is changed
for $i = 0$ to $i < n - 1$ **do**
$awnd_i = round(\frac{x_i}{\sum_{j=0}^{n-1} x_j} * A)$
$cum\_awnd = cum\_awnd + awnd_i$
end for
$awnd_{n-1} = A - cum\_awnd$

Figure 4.1: Receiver Window Control

4.2 RWC Simulations

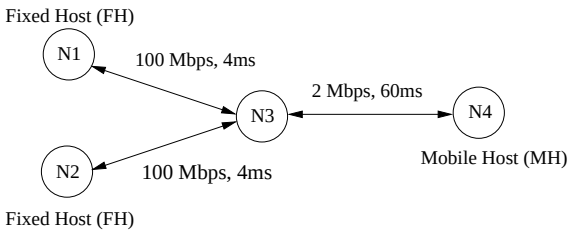


Figure 4.2: RWC: Simulation setup

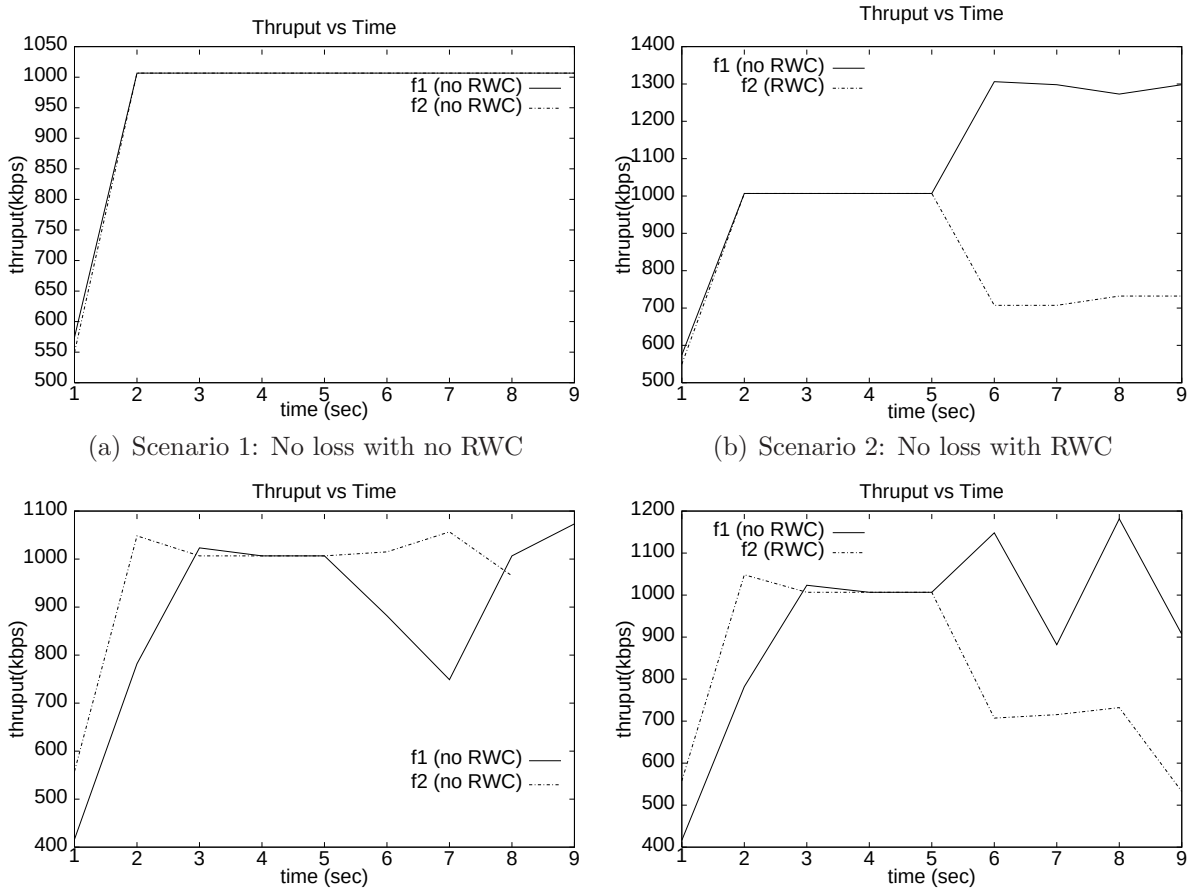
The simulation setup is shown in Figure 4.2. Two ftp[1] flows, f_1 and f_2, were run from the two fixed hosts, N1 and N2 respectively. The mobile host (MH) is the receiver. User feedback was simulated by setting the `window_` (window underscore) parameter of the TCP senders on N1 and N2, 5 seconds after start of simulation. The initial priorities were assumed to be: $x_1 = 1$ and $x_2 = 1$. For the simulation set-up $A = 32$ packets. Thus from Figure 4.1, $awnd_1 = 16$ and $awnd_2 = 16$. After feedback, let $x_1 = 2$ and $x_2 = 1$. Hence, from Figure 4.1, $awnd_1 = 11$ and $awnd_2 = 21$. The `window_` parameter of the senders on N1 and N2 were set to these values, respectively.

One set of simulations was done assuming no losses on the links. A second set was done, assuming a loss of 0.1% on the link N3-N4. Each simulation run was of 9 seconds duration.

[1]File Transfer Protocol

4.2.1 RWC Simulation Observations

- *Scenario 1: No loss with no RWC* – (Figure 4.3(a)). As expected the throughput of both f_1 and f_2 is equal, each $\approx$ 1 Mbps.
- *Scenario 2: No loss with RWC* – (Figure 4.3(b)) the throughput for f_1 increases to $\approx$ 1.31 Mbps (increase by 31%) and that for f_2 decreases to $\approx$ 0.69 Mbps (decrease by 31%).



(a) Scenario 1: No loss with no RWC

(b) Scenario 2: No loss with RWC

(c) Scenario 3: 0.1% loss with no feedback

(d) Scenario 4: 0.1% loss with RWC

Figure 4.3: RWC: Simulation results

- *Scenario 3: 0.1% loss with no RWC* – (Figure 4.3(c)) shows the throughput of both the applications under lossy link conditions. The variations in throughput are due to the random losses. However, the throughput of both the flows is approximately equal.
- *Scenario 4: 0.1% loss with RWC* – (Figure 4.3(d)) user feedback has the effect of increasing the throughput for f_1, even though there are some packet losses.

In the previous sections, we discussed the RWC algorithm, RWC simulations and observations. We now describe the prototype implementation of RWC using ECLAIR.

4.3 Receiver Window Control Implementation using ECLAIR/Linux

The high level design of RWC using ECLAIR is presented in Chapter 3, Section 3.4.1 (Figure 3.3). Next we present the implementation details.

4.3.1 Receiver Window Control Implementation Details

First we present some of the internal details of the Linux TCP/IP kernel which are relevant for Receiver Window Control implementation using ECLAIR. We chose Linux since its source code is freely available and modifiable.

Figure 4.4 shows the relevant data structures in `sock.h`. The numbers on the left identify the relevant code. `tcp_opt` (line number 1) is TCP's control data structure. `sock`

```
1    struct tcp_opt {
       .
       .
                    /* Maximal window to advertise */
2                   __u32   window_clamp;
                    /* Current window clamp        */
3                   __u32   rcv_ssthresh;
       .
     }

4    struct sock {
       .
       .
5                union {
6                         struct tcp_opt          af_tcp;
                          .
                          .
                      }
     }
```

Figure 4.4: /usr/src/linux-2.4/include/net/sock.h source code snippet

(line number 4) is the *socket* data structure. Line numbers 2 and 3 show `window_clamp` and `rcv_ssthresh` which are used for controlling the advertised window in TCP. We identified these data structures by studying the TCP implementation in Linux kernel 2.4.x [101]. For browsing the Linux kernel code, we used source code browsing tools such as cscope [94], cbrowser [92] and the Linux Cross Reference website [93].

Figure 4.5 shows the call flow of our implementation using ECLAIR. The current implementation has largely TL functionality only. In this prototype the RWC *calculation*

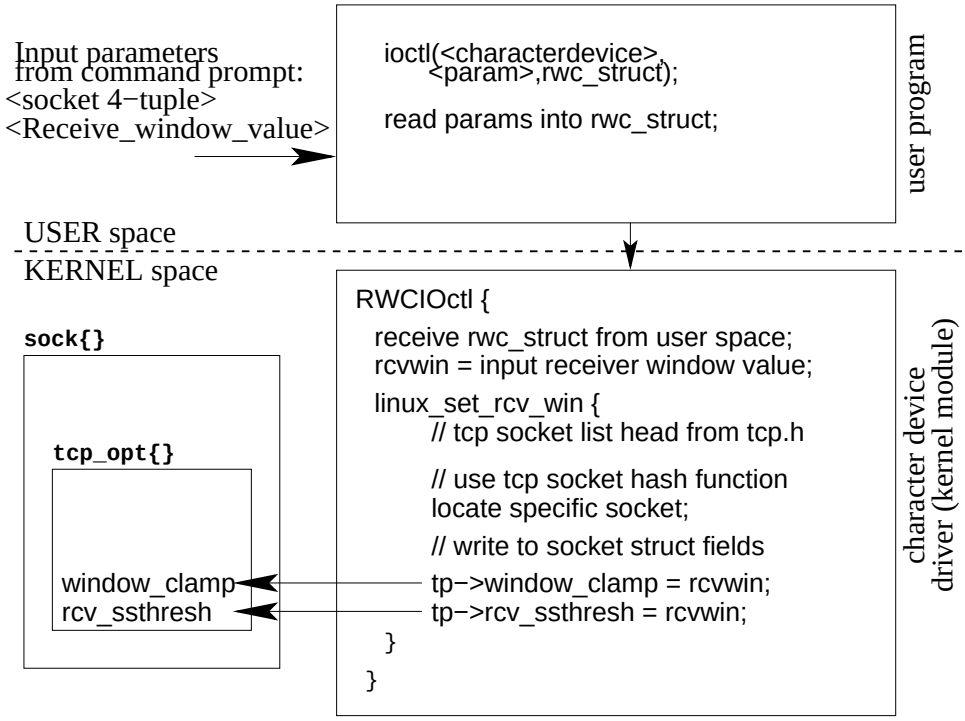


Figure 4.5: Call flow: RWC using ECLAIR

is done by the user. The user runs a program in user-space with the parameters: *socket 4-tuple* (sender port and address, destination port and address, to identify the application) and the receiver window value. These parameters are passed to the TL, in `rwc_struct` via `ioctl`, to change the control parameters (receiver window) in the socket. The socket 4-tuple parameter is used to identify the application's TCP socket within which the receiver window value is to be changed. We implemented the receiver window control TL as a Linux kernel loadable module [23]. No modification was required to the TCP code in the kernel.

Figure 4.6 shows relevant code of the module. Line 1 shows the character device major number. Line 2 shows the *ioctl* number code. This is used by the `ioctl` function for invoking the RWC module. The upper half of the figure, above the dotted line, is the PO. In lines 11-12, the PO registers for user events, as a *character device* with the name `ioctl-rwcDriver`. The user process writes to this character device using `ioctl`. In the lines 9,10, in the structure `ioctlFops`, the function (character device driver) `RWCIOctl` is declared. This function will be invoked in the module, when `ioctl` calls this module. The function `RWCIOctl` is defined in the lines 3-8. At line 3, `switch` checks the ioctl parameter passed from the ioctl function. We have only shown the relevant case. At line 5, the parameters passed by the user, from the command line, are readinto a structure `rwc_ioctl_param`. The structure `rwc_info_struct` is defined in a separate header file and is used for holding the parameters to be passed from the user space to kernel space. At line

```
1     #define IOCTL_MAJOR 250
2     #define IOCTL_GETVALUE 0x0001
      ...
3     static int RWCIOctl(...)
      {
          ...
          switch( cmd ) {
4         case IOCTL_GETVALUE:
5             rwc_ioctl_param = (struct rwc_info_struct *) arg;
              // copy socket 4-tuple to socket_info
6             socket_info.s_addr =
                              rwc_ioctl_param->in_ip_addr.s_addr;
              ...
7             rwc_window = rwc_ioctl_param->rwc_window;

              // TCP TL function
8             linux_set_recv_win (socket_info, rwc_window);
          ...
      }
9     static struct file_operations ioctlFops = {
      ...
10        ioctl: RWCIOctl,  /* ioctl */
      };

11    static int __init IoctlRWCInit(void)
      {
          printk(KERN_ERR "TCP RWC func load.\n");
12        if(register_chrdev(IOCTL_MAJOR,
                  "ioctl-rwcDriver", &ioctlFops) == 0) {
          ...
          };
          printk("ioctl: unable to get major %d\n",IOCTL_MAJOR);
          return( -EIO );
      }
-------------------------------------------------------------------
13    linux_set_recv_win (socket_info, rwc_window)
      {

14        // locate socket using socket_info and copy of tcp_hashfn
15        struct tcp_opt *tp = &(sk->tp_pinfo.af_tcp);
16        lock_sock(sk);
17        tp->window_clamp = rwc_window;
18        tp->rcv_ssthresh = rwc_window;
19        release_sock(sk);
      }
```

Figure 4.6: rwc_user.c source code snippet. RWC PO and TL

8, the parameters socket 4-tuple (sender address and port, destination address and port), and receiver window value are passed to the TCP TL function `linux_set_recv_win`. The function `linux_set_recv_win` is defined from lines 13-19. At line 14, the relevant socket is located using `tcp_hashfn`. Code for this function is available in the Linux kernel source code file `/usr/src/linux-2.4/net/ipv4/tcp_ipv4.c`. At line 15, the tcp information structure is extracted from the socket structure. From lines 16-19, the socket located above is locked for writing, tcp structure's `window_clamp` and `rcv_ssthresh` is updated to set the receiver window value and finally the socket lock is released.

Next, we present the details of the RWC-ECLAIR experiments over wireline and WLAN. A detailed evaluation of ECLAIR overheads is presented in Chapter 5.

4.4 RWC Experiments

4.4.1 Experiments over Ethernet LAN

The first set of experiments were done on Ethernet LAN to rule out any variations due to the wirelss connection. The aim of these experiments was to do a basic test that the RWC implementation is functioning correctly. Figure 4.7 shows the experimental setup. All the machines were on the IIT Bombay campus LAN. The link N3-N4 bandwidth is 1 Mbps. Two flows *Flow 1* and *Flow 2* were started from N1 (cygnus) and N2 (gitanjali), respectively, to N4 (sarus). The flows were started simultaneously in the background using `wget` on N4. A file of appox. 9MB was transfered from both N1 and N2 using `http`. Receiver Window Control was implemented on the node N4.

Figure 4.8(a) shows the results when RWC was not invoked. Both the flows had almost equal throughput. The variations are due to competing traffic on the network. Figure 4.8(b) shows the results when RWC was manually invoked at about 8 seconds. We invoked RWC with a receiver window size of 1450 bytes, on Flow 1. Figure 4.8(b) shows that the throughput of Flow 1 decreases while that of Flow 2 increases. The throughput of Flow 1 increases slightly after the file transfer of Flow 2 ends.

The results are as expected and validate our implementation of Receiver Window Control. Subsequent to the Ethernet LAN experiments we carried out experiments over a 802.11 wireless network. The wireless experiment setup and results are presented below.

4.4.2 Experiments over 802.11 Wireless Connection

Figure 4.9 shows the experimental setup. For our experiments we used a Air Premier D-Link Enterprise 2.4GHz Wireless Access Point – DWL-1000AP+ (managed mode), and D-link 520+ Wireless PCI Adapter (2.4 GHz) [96] on the desktop (Intel Pentium4 CPU,

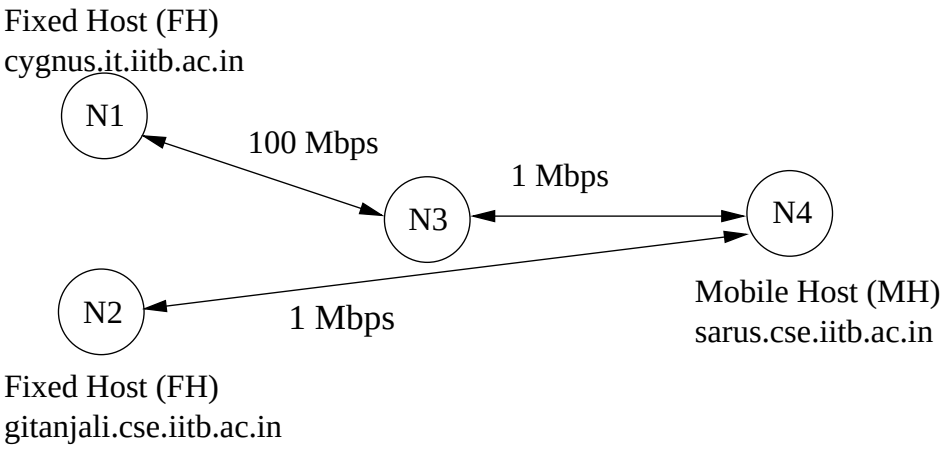
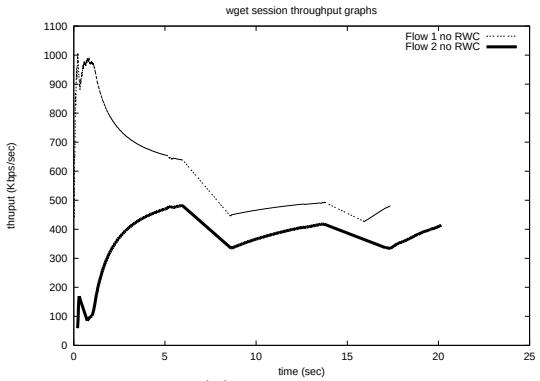
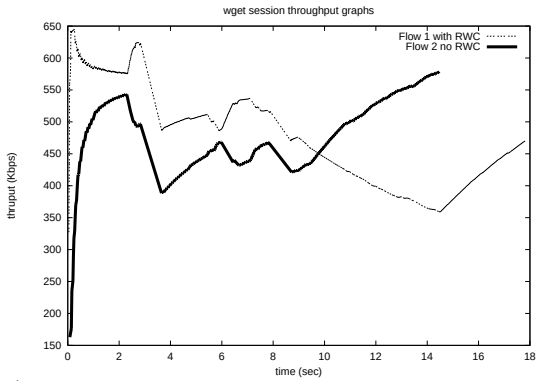


Figure 4.7: RWC: Experiment setup



(a) No RWC



(b) RWC: Receiver Window value = 1450 bytes, invoke time = 8 sec

Figure 4.8: Receiver Window Control experiments over wireline (Ethernet)

1.90GHz, 256 MB RAM, 256KB cache) which had the RWC implementation. To match the environment characteristics, we set the *sensitivity* of the WLAN card to 60 using the script available with the driver package [90, 91]. Sensitivity is the lowest signal level for which the hardware will consider received packets usable. Sensitivity is the threshold set for Received Signal Strength Indicator (RSSI). This is set based on the average noise level to avoid reception of noise. The card sensitivity was set to 60 on a scale of 255 (maximum value). We used the default MTU[2] of 1500. For our experiments:

- We ran two *wget* [3] *http* [4] sessions from MH to FH1 and FH2. The file size downloaded was 2MB each.
- We invoked RWC from the command prompt during the http transfer, with different receive window values.

[2]Maximum Transmission Unit
[3]Wget is a network utility to retrieve files from the Web using http and ftp
[4]Hyper Text Transfer Protocol

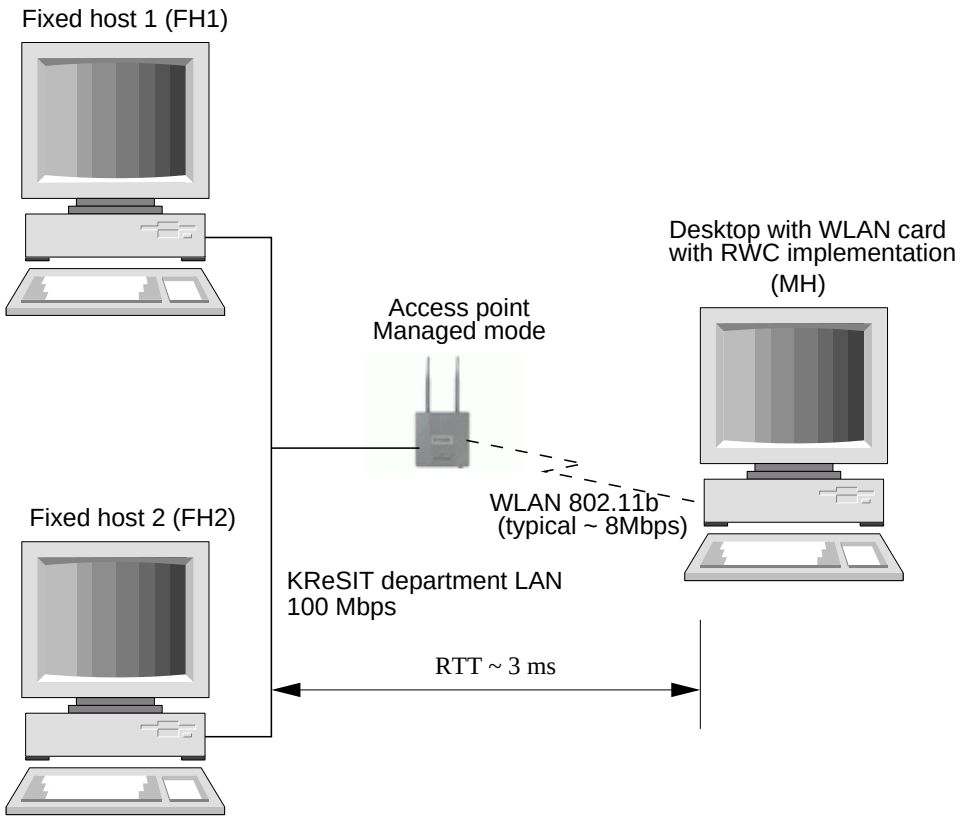


Figure 4.9: RWC: Experiment setup

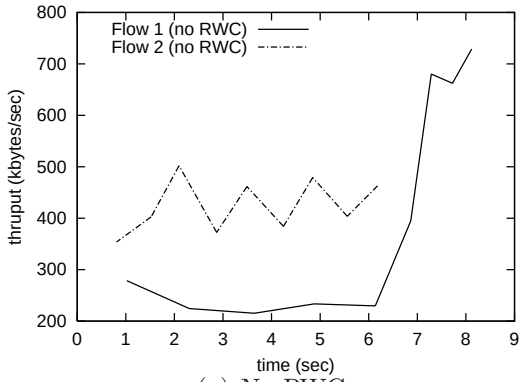
- We carried out four experiments. Each experiment was repeated 3 times.
  - In the first experiment, RWC was not invoked.
  - In the other three experiments, RWC was invoked with receiver window values of 2KB, 1KB and 0.5KB. For each receiver window value, RWC was invoked at 1, 2 and 5 seconds.

We have shown representative results in Figure 4.10. The graphs of the other runs are similar. We have not taken averages of the results, since there were wide fluctuations in throughput due to the wireless medium.

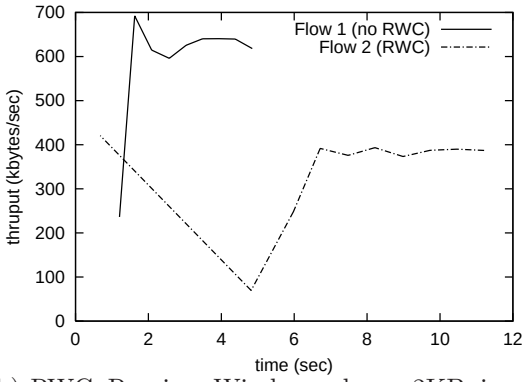
Table 4.1 shows the mean and standard deviation of the throughput for Flows 1 and 2 across various runs.

RWC Experiment Observations

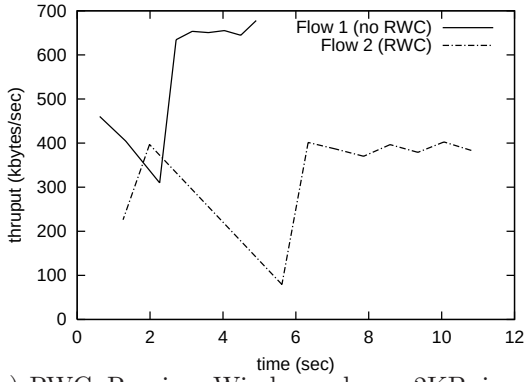
For the experimental setup the approximate bandwidth-delay product is 3KB. (8000/8 KBps * 3/1000 sec, see Figure 4.9). Thus to throttle a sender the receiver window should be less than 3KB. Since network packet losses are expected in a WLAN, we started with a receiver window of 2KB.



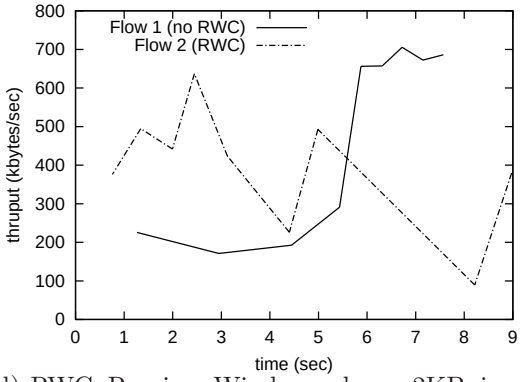
(a) No RWC



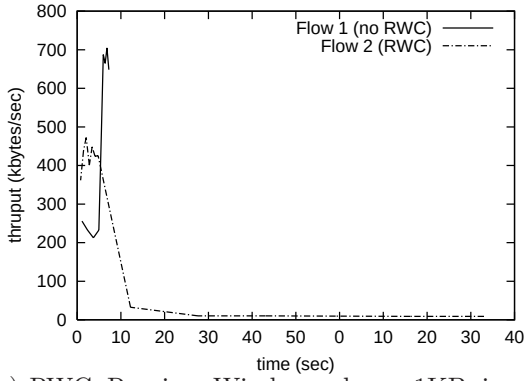
(b) RWC: Receiver Window value = 2KB, invoke time = 1 sec



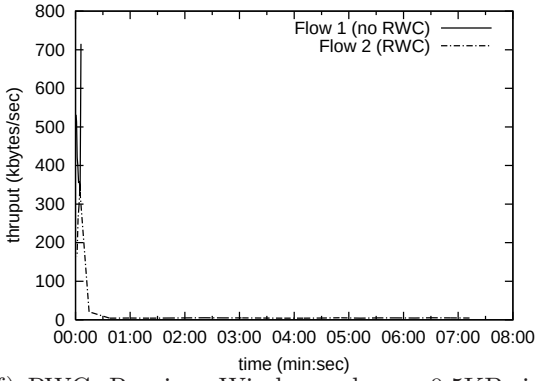
(c) RWC: Receiver Window value = 2KB, invoke time = 2 sec



(d) RWC: Receiver Window value = 2KB, invoke time = 5 sec



(e) RWC: Receiver Window value = 1KB, invoke time = 5 sec



(f) RWC: Receiver Window value = 0.5KB, invoke time = 5 sec

Figure 4.10: Receiver Window Control experiments over WLAN (802.11)

Table 4.1: Mean and standard deviation of Flow 1 and 2 throughput

		Flow 1	*Flow* 1	*Flow* 2	*Flow* 2
RWC invoked at (seconds after start)	Receiver Window Size (bytes)	$\bar{X}$ *kbytes/s*	σ *kbytes/s*	$\bar{X}$ *kbytes/s*	σ *kbytes/s*
Not invoked	–	304·06	23·77	383·64	23·20
1	2048	543·42	15·76	243·36	3·96
2	2048	488·58	35·14	252·82	1·75
5	2048	347·93	4·98	277·98	6·03
1	1024	547·37	20·21	8·30	·37
2	1024	521·23	29·13	8·95	·64
5	1024	379·13	18·92	21·44	8·18
1	512	580·60	19·57	4·03	·034
2	512	541·45	26·40	4·44	·36
5	512	413·89	20·91	8·18	1·61

- *Scenario 1 - No RWC (figure 4.10(a)):* The default bandwidth available to the flows is shared unequally. The flow that starts first gets most of the bandwidth.
- *Scenario 2 - RWC*: We reduced the receive window of one of the flows. The default (system) receive window is 64KB (default in Linux). This is much larger than the bandwidth-delay product, hence we did not increase the receive window of the other flow.
  - *Receive Window 2KB (figures 4.10(b) - 4.10(d)):* As expected, in each of the cases Flow-2 is throttled due to the reduced receive window.
  - *Receive Window 1KB/0.5KB (figures 4.10(e) - 4.10(f)):* Due to further reduction in the receive window, the bandwidth available to Flow-2 is reduced much more as compared to the previous scenario.

Analysis of Experimental Results

ECLAIR validated:
The RWC experimental results are in-line with the simulation results presented in Section 4.2. Thus, the experimental results show that the ECLAIR implementation works as expected. The throughput reduces for the flow that is controlled through RWC and that of the other flow increases, even in the presence of packet losses on the wireless medium. This validates the ECLAIR implementation.

Differences between experimental and simulation results:
There are some differences between the experimental and simulation results. The differences and the reason for the difference is as follows: (1) In case of simulation, we had run a *continuous* transfer using *ftp* and stopped the simulation after 9 seconds. In case of the experiment, we transferred a file using *wget* and stopped the experiment after both the transfers (Flow-1 and Flow-2) had completed. (2) When RWC is not invoked, the simulation shows an equal distribution of bandwidth between the two flows. In case of the experiment on WLAN, due to the characteristics of the wireless interface and environment, the flow that starts first gets most of the bandwidth. (3) In the experiment, after RWC is invoked, throughput of the controlled flow remains low even after the uncontrolled flow completes the file transfer. This is because of the way we have implemented RWC – we do not reset the value of the receiver window to the default of 64KB. It can be seen that the differences between experimental and simulation results are not significant and hence do not impact the validation result, stated above.

4.5 Summary

In this chapter we presented our prototype ECLAIR implementation for receiver window control. We explained the details of the implementation using code snippets. We validated the prototype implementation by experiments over a WLAN.

The RWC prototype is sufficient to validate ECLAIR, due to the following: (1) It shows that a protocol's (TCP's) behavior can be modified by manipulating the control data structure. Similarly, the modification of protocol behavior can be done for protocols of other layers also. (2) Although, the input in this prototype is from the user, the input can easily be provided by any other PO that needs to modify TCP behavior.

In the next chapter we evaluate ECLAIR.

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There is nothing either good or bad, but thinking makes it so
- William Shakespeare

Chapter 5

ECLAIR Evaluation

In the previous chapter we discussed the implementation of ECLAIR and its validation through an illustrative example – RWC. This chapter has four parts – metrics definition, qualitative evaluation, quantitative evaluation and overhead measurement. In Section 5.1, we identify a set of metrics for evaluating a cross layer architecture against the design goals defined in Chapter 2. In Section 5.2, we use these metrics to qualitatively compare ECLAIR with the other cross layer feedback approaches which were presented in Chapter 2. In Section 5.3, we quantitatively compare ECLAIR and user-space [54] implementations of Receiver Window Control (RWC). In Section 5.4, we measure ECLAIR overheads by instrumenting the Linux kernel, and compare it with user-space architecture and architectures which propose modification to the protocol stack.

5.1 Evaluation Metrics

In Section 2.5 we stated that the design goals for a cross layer architecture are *efficiency*, *maintainability*, *minimum intrusion*, *portability* and *any to any layer communication*. Metrics are essential to evaluate a cross layer architecture against these goals. Below we propose metrics for each of these design goals. The metrics are classified into two categories – efficiency and maintainability.

For any-any layer communication, a subjective evaluation is sufficient to determine whether an architecture supports it or not. Hence, no specific metric is required for this design goal.

5.1.1 Efficiency Metrics

We define efficiency as *runtime* and *static* efficiency. An architecture A_1 has more run-time efficiency than an architecture A_2, if A_1 requires lesser computing resources at run-time as compared to A_2. Similarly, architecture A_1 has more *static* efficiency than an architecture A_2, if it requires lesser static resources as compared to A_2.

Cross layer feedback is essentially a modification to the protocol stack. The intent is to enhance performance of the stack by reading information from a layer, interpret that information and effect a change at another layer. However, effecting cross layer feedback entails the overhead of running additional instructions or programs, in the kernel or user-space. In light of this, we define the following as the primary performance measures for efficiency:

- *Time* overhead: This is the CPU cycles or execution time required

- *Space* overhead: This has two components: (1) the run-time memory required by the cross layer algorithm because of the architecture, and (2) the *static footprint* of the cross layer implementation.

- *User-kernel crossing:* This is the number of times user-kernel *boundary* needs to be crossed during execution.

  User-kernel crossing could contribute significantly to the run-time overhead of cross layer feedback. Hence, we also consider the number of user-kernel crossings as an important efficiency metric. User-kernel crossing is an important metric since it requires a *significant* number of CPU cycles for switching from user to kernel mode. Any system call requires switching from user to kernel mode. This typically requires the system call library wrapper function to issue a software-interrupt. Subsequent to this copying of data from user-space to kernel-space is required for parameter passing. Similarly, copying from kernel to user-space is required for passing values to the user-space. System call processing is explained in detail in reference [13].

- *Data path delay:* This is the delay introduced in the *data path* of the stack, due to cross layer feedback.

  Data path is the sequence of functions within the protocol stack which are concerned only with sending and/or receiving packets. *Data path delay* means the time delay on the data path. Data path delay would include a whole or part of time overhead and user-kernel crossing overhead of a cross layer feedback mechanism. However, since it directly impacts the throughput of the stack, we list it as an independent efficiency metric.

5.1.2 Maintainability Metrics

Maintainability is a measure of the ease with which a system can be changed or enhanced [62]. There is no direct means of measuring maintainability. One of the indirect measures is the time taken to *change* a system. However, this can be done only when the system has been deployed. For predicting maintainability at the architecture level, architecture evaluation techniques such as Architecture-level Modifiability Analysis (ALMA) [9] or Software Architecture Analysis Method for Evolution and Reusability [51] can be used. Both these methods propose a *scenario* based analysis of the architectures for maintainability. A scenario describes a change that may be required to the system. The changes required to the various components for implementing the scenario are determined. The overall impact is assessed to determine the architecture's maintainability.

For a cross layer feedback architecture maintainability can determined by assessing the capability of the architecture to support *rapid prototyping*, *minimum intrusion* and *portability* (Section 2.5).

Rapid Prototyping Metric

Rapid prototyping, as the name implies, should allow introduction of new cross layer feedback algorithms or changes to the existing cross layer algorithms with *minimal* changes to the system. The effort required to add or modify a cross layer optimization, that is, number of changes required to the protocol stack and number of changes required to the cross layer system serve as a measure for rapid prototyping.

Degree of Intrusion Metric

Degree of intrusion can be measured by the number of changes required within the existing protocol stack, to implement a cross layer optimization.

Assume, x changes are required to the existing stack to implement a cross layer optimization for architecture A_1 while y changes are required for the same optimization if architecture A_2 is used. If the changes x and y are of similar nature, then if $y < x$, A_2 has *lesser intrusion* than A_1. For example, if Receiver Window Control is implemented using CLASS [79], then the number of changes required to the protocol stack will be higher as compared to the case when ECLAIR is used. Thus, the degree of intrusion of ECLAIR is less than that of CLASS.

Portability Metric

Portability can be measured by the number of changes required within a cross layer implementation to port it to another operating system. Portability is high if porting requires minimum changes to the cross layer optimization.

We believe that the above metrics are sufficient to evaluate any cross layer architecture. We use these metrics to evaluate ECLAIR. In the next section, we carry out a qualitative comparison of ECLAIR with the other cross layer feedback mechanisms.

5.2 Qualitative Evaluation

In this section we do a qualitative comparison of ECLAIR with the other cross layer feedback approaches. Details about the cross layer approaches have been presented in Chapter 2. We exclude Cross Layer Manager [17] from the evaluation since sufficient details about the architecture are not available. For each of the approaches we discuss the features which are relevant for a particular metric. We then rank each approach.
Ranking order: Rank 1 for an approach means that approach is the best as compared to others, for a particular metric.

5.2.1 Efficiency Evaluation

Recall that the metrics for efficiency are: time overhead, space overhead, user-kernel crossing and data-path delay (Section 5.1.1).

Time Overhead Evaluation

Here we analyze the time overhead that a cross layer approach would place on the system.
Metric:
As stated in Section 5.1.1, time overhead means the CPU cycles or execution time required.
Analysis:
We analyze the mechanism for event notification and the protocol adaptation technique. We assume that the time taken by the adaptation algorithm, that is, determination of the actual adaptation for a protocol would be similar for all the approaches. Hence we do not include this for the evaluation. Table 5.1 shows the time overhead evaluation. Each row shows an architecture, factors contributing to time overhead in that architecture, and a relative rank for the architecture.
Key observations:
ISP [81] has the least time overhead. Since, it passes event information in the packet header and it does not require much processing time for event creation and cross layer feedback. Further, cross layer event processing is tightly integrated with the packet processing.

ECLAIR rank is 3, since it needs CPU cycles to monitor a protocol, deliver the event and process the event separate from the stack processing.

Table 5.1: Time overhead comparison

Cross Layer Approach	**Time overhead factors**	**Rank**
PMI [34]	(1) Guard modules monitor devices; generate events. (2) Events delivered to device manager. (3) From device manager, event propagates layer by layer, through *each* adaptation module. (4) Operating system call modified to trap user inputs to devices. This adds to overhead.	4
ICMP Messages [73]	(1) Monitoring and generation of events by a module. (2) Event propagation using ICMP messages. (3) Within message handler: message parsing, scanning of application and transport layer action tables, message delivery to application layers. (4) Adaptation by transport layer and application.	5
MobileMan [21]	Actions within each modified protocol: (1) Updating and reading network information from Network Status using its APIs. (2) Parsing of information read and adaptation.	2
CLASS [79]	Actions within each modified protocol: (1) Invoking APIs of other layers' protocols to pass its requirements. (2) Generating event; passing event information to other layers' protocols by invoking their APIs. (3) Adaptation on receipt of event.	2
ISP [81]	Actions within a protocol: (1) Embedding cross layer information within a packet. (2) Parsing packet (at all layers' protocols) for cross layer information from upper layer. (3) Adaptation based on information in packet.	1
User-space [54]	(1) Monitoring of stack in kernel-space by a module. (2) Generation of event; delivering to user-space modules. (3) Adaptation by user-space modules using operating system APIs.	2
ECLAIR	(1) Monitoring of protocol in a layer by Tuning Layer (TL). (2) Generation of event by TL; delivery to all registered Protocol Optimizers (PO) within kernel; delivery of event to POs in user-space (if any). (3) Adaptation by POs; adaptation executed by invoking generic TL APIs which in turn invoke implementation specific APIs.	3

Space Overhead Evaluation

We now analyze the space overhead of a cross layer implementation.

Metric:

As stated in Section 5.1.1, the space overhead is a measure of the *run-time* memory required and *static footprint* of the cross layer implementation.

Analysis:

We estimate the space required for the various components (binary files). We also estimate the space required by the various data structures during runtime. The binary files would also add to the runtime space overhead, while executing.

Table 5.2: Space overhead comparison

Cross Layer Approach	**Space overhead factors**	**Rank**
PMI [34]	*Runtime:* State machine maintained for each device. *Static:* (1) Guard modules for monitoring interfaces, costs, network connection. Modification to operating system call for user events. (2) Device manager for receiving events and passing to adaptation modules. (3) Adaptation modules.	3
ICMP Messages [73]	*Runtime:* (1) Socket created by each application for event information. (2) ICMP messages carrying events. (3) Action tables for application and transport layer adaptation. (4) Modified device data structure. *Static:* (1) Device event monitors. (2) ICMP message generator; ICMP message handler at socket layer. (3) Adaptation code within each layers' protocols	5
MobileMan [21]	*Runtime:* Event information stored in Network Status component. *Static:* (1) Network status component. (2) Code added to a requisite protocols for event reading and writing from Network Status. (3) Adaptation code within a protocol at a layer.	2
CLASS [79]	*Runtime:* Event information passed between the layers. *Static:* Within a layer's protocol (1) Adaptation code. (2) Code for parameter reading and setting. (3) Event generating code. (4) APIs added enable interaction with other layers' protocols.	2
ISP [81]	*Runtime:* Cross layer information embedded within a packet. *Static:* Within a protocol at a layer (1) Code for parsing the information embedded in packet. (2) Adaptation code.	1
User-space [54]	*Runtime:* (1) Data structure for list of registered applications. (2) Memory required for user-kernel, and kernel-user, message passing. *Static:* (1) Adaptation modules. (2) Modules for receiving events from kernel-space	3
ECLAIR	*Runtime:* (1) Data structure within each TL for list of registered Protocol Optimizers. (2) Event information passed from TL to PO. (3) Memory required for user-kernel, and kernel-user, message passing. This is for interaction with user and application TLs/POs which may be in user space. *Static:* (1) Code for monitoring and generating events, within TL (2) Code for generic and implementation specific APIs, within TL. (3) Adaptation code within the POs.	4

We assume that the space required by the adaptation algorithm, that is, algorithm that determines the actual adaptation for a protocol, would be similar for all the approaches. Table 5.2 shows the space overhead evaluation. Each row shows an architecture, factors contributing to space overhead (runtime and static) in that architecture, and a relative rank for the architecture.

Key observations:
ISP [81] has the least run-time overhead since all the event information is embedded within the header. Further, no memory is required for maintaining a list of interested layers. Also, no separate modules are created for adaptation, the adaptation code is embedded within the protocol stack.

ECLAIR rank is 4. This because during run-time each TL needs to maintain lists of POs which are interested in events. Further, the static footprint of ECLAIR is also higher since it requires creation of multiple TL and PO modules. Also, extra code is required for generic and implementation specific interfaces.

User-Kernel Crossing Evaluation

We now analyze the user-kernel crossing overhead of a cross layer implementation.
Metric:
Recall from Section 5.1.1, that user-kernel crossing metric is the number of times the user-kernel boundary is crossed during execution.
Analysis:
Here we estimate the number of user-kernel crossings which would occur, during runtime, if a particular cross layer approach is used. Table 5.3 shows the user-kernel crossing evaluation. The table shows the factors contributing to user-kernel crossing for an architecture and the relative rank for an architecture.
Key observations:
ISP [81] ranks the best. It requires no separate user-kernel crossing, since the cross layer information is embedded within the packet header.

ECLAIR rank is 2. This is because ECLAIR requires some amount of user-kernel crossing for communicating information from user and applications to kernel and vice-versa.

Data Path Delay Evaluation

We now analyze the data path delay overhead of a cross layer implementation.
Metric:
As stated in Section 5.1.1, data path delay is measured by the delay introduced in the data path of the stack due to cross layer feedback.
Analysis:
We assume that the adaptation algorithms are same for all the approaches. We highlight the processing tasks that would impact the data path. Table 5.4 shows the data path delay evaluation. The table shows factors contributing to data path delay and relative ranking of the architectures. For architectures such as MobileMan [21], CLASS [79] and

Table 5.3: User-kernel crossing comparison

Cross Layer Approach	**User-Kernel crossing factors**	**Rank**
PMI [34]	User-kernel crossing depends on placement of device manager. Prototype shows device manager implemented in user-space. Factors: (1) Passing device *guard* information to device manager (kernel to user-space). (2) Checking status of each device at regular intervals (user to kernel). (3) Passing adaptation information from device manager to kernel using operating system APIs (user to kernel). (4) Information passing to/from application adaptation module (user-kernel and vice versa). If device manager is in kernel, the user-kernel crossing will reduce. However, point number (4) will still be applicable.	3
ICMP Messages [73]	(1) Definition of transport adaptation action, by each application (user to kernel). (2) Delivering events to interested applications (kernel to user).	2
MobileMan [21]	Application's *read* or *write* to Network Status component (user to kernel).	2
CLASS [79]	(1) Each application passing its QoS requirements to lower layers (user to kernel-space). (2) Events and other information from lower layers delivered to applications (kernel to user-space).	2
ISP [81]	No additional user-kernel crossing since information is embedded within the packet headers.	1
User-space [54]	(1) Adaptation of protocols using operating system APIs (user to kernel). (2) Passing event information to user-space modules (kernel to user).	3
ECLAIR	(1) Passing information from user or application to kernel space (user to kernel). (2) Passing event information to application or application PO in user-space (kernel to user).	2

ISP [81], since the cross layer implementation is entirely within the protocol stack, the data path delay factors are the same as those for time overhead, stated in Table 5.1.

Key observations:
ECLAIR rank is 1, because ECLAIR components (TLs and POs) are not embedded within the stack.

ISP [81] is at rank 4. This is because, a layer needs to modify the packet header, for passing cross layer information. Further, all layers below need to parse this packet and carry out adaptation if required. All this, decreases the stack execution speed and hence leads to increased data path delay.

Above we evaluated efficiency of various cross layer feedback approaches. Next, we evaluate maintainability of the cross layer approaches.

Table 5.4: Data path delay comparison

Cross Layer Approach	**Data path delay factors**	**Rank**
PMI [34]	No data path delay, since all adaptation is from outside the stack.	1
ICMP Messages [73]	Adaptation code is introduced within the existing protocol implementation. Additional protocol variables are introduced. (1) Protocol execution slows down since additional variables need to be checked. (2) Appropriate adaptation needs to be done within the protocol. (3) Event delivery through special ICMP messages. IP and TCP protocols will have to handle these additional packets, impacting speed of processing application data packets.	2
MobileMan [21]	Same as that for time overhead (Table 5.1). Within each modified protocol: interaction with the Network Status component and protocol adaptation.	3
CLASS [79]	Same as that for time overhead (Table 5.1). Within each modified protocol, interaction with other protocols, event generation and event passing and protocol adaptation.	3
ISP [81]	Same as that for time overhead (Table 5.1). Within each modified protocol – encoding information in packet, parsing packet and protocol adaptation.	4
User-space [54]	Depends on implementation of adaptation modules. If event monitoring, delivery and adaptation is built into the application or some system library on data path, then data path delay is high. An example is, RWC implementation as specified in reference [54]. If the adaptation modules are not on the data path then the delay could be low.	3
ECLAIR	No data path delay, since all adaptation is from outside the stack.	1

5.2.2 Maintainability Evaluation

Rapid prototyping and Degree of Intrusion metrics have similar characteristics. Both measure the number of changes required to the system for implementing cross layer feedback. In light of this, we combine the analysis of these two metrics.

Rapid Prototyping Evaluation

In Section 5.1.2, we defined rapid prototyping as the ease with which a cross layer optimization can be added, deleted or changed.

Metric:
The number of changes required to the protocol stack and the number of changes required to a protocol optimization algorithm, is an indicator of the ease of rapid prototyping.

Degree of Intrusion Evaluation

Degree of intrusion can be estimated by the modifications needed to the protocol stack for introducing a cross layer feedback optimization.

Analysis:
We assume that some cross layer algorithm needs to be implemented or changed. For this cross layer algorithm, we then estimate the number of changes that would be required to the protocol stack or the cross layer system. Table 5.5 shows the rapid prototyping and degree of intrusion evaluation. The table presents the factors which determine rapid prototyping and degree of intrusion of an architecture.

Key observations:
User-space [54] ranks 1 for both rapid prototyping and degree of intrusion. This is because all the modules are implemented in user-space and the system calls provided by the operating system are used for interacting with the protocol stack. Thus, no changes are required to the protocol stack. Also, due to these reasons changes can be easily implemented.

ECLAIR rank is 2 for rapid prototyping and 2 for degree of intrusion. This is because, a large part of ECLAIR needs to be implemented in the kernel. Further, some changes may be required to the protocol stack for enabling access to some protocol control data structures. See Chapter 3, Section 3.2 for an overview of accessibility to protocol stack data structures.

Portability Evaluation

Metric:
As stated in Section 5.1.2, portability is measured by the number of changes required to a cross layer implementation, for porting it to another operating system.

Analysis:
We estimate the number of changes required to the cross layer modules, to port it to a new operating system. For architectures in which the cross layer algorithm is implemented within a layer, the layer would need to be modified. Table 5.6 shows the portability evaluation.

Key observations:
ECLAIR rank is 1. This is because ECLAIR provides a generic API which is exported by the TL to the PO. This generic API invokes the implementation specific API. For porting to a new operating system, only the implementation specific API needs to be added.

Architectures such as MobileMan [21] and CLASS [79], require modifications to the protocol stack and hence rank lower than ECLAIR.

Table 5.5: Rapid Prototyping capability and Degree of Intrusion comparison

Cross Layer Approach	**Rapid Prototyping (RP) and Degree of Intrusion (DoI) analysis**	**RP Rank**	**DoI Rank**
PMI [34]	*Changes to protocol stack*: None. *Changes to existing modules:* (1) *Adaptation Layers* to enable new adaptation. (2) *Guard modules* for adding new events.	2	1
ICMP Messages [73]	*Changes to protocol stack:* (1) *Protocol* for (a) addition of new parameters, (b) addition of adaptation code. *Changes to existing modules:* (1) *All applications* to enable definition of new adaptations for protocols. (2) *ICMP message generator* to create new events. (3) *ICMP message handler*, in the socket layer to update new variables defined for the protocols.	4	3
MobileMan [21]	*Changes to protocol stack:* (1) *Protocol* for introducing new optimization or event. For new events: (2) *Network Status* component. (3) *All* the *protocols* which would use the new event. *Changes to existing modules:* As above, since all the modules are within the protocol stack. Further, changes may be required to applications to handle the new or modified event.	4	4
CLASS [79]	*Changes to protocol stack:* (1) *Protocol* changed to introduce new optimization or event. (2) If any API of a protocol p is modified or a new API or event is introduced, changes are required to all protocols interacting with p. *Changes to existing modules:* As above, since all the modules are within the protocol stack. Changes may be required to applications to handle the new or changed event.	5	4
ISP [81]	*Changes to protocol stack:* If new adaptation information added in packet header, modification required to (1) *Protocol* to embed new information in the packet. (2) *All* lower layer *protocols* that intend to use the new (or changed) information. This is required to enable parsing of the packet and subsequent adaptation. *Changes to existing modules:* As above, since all the modules are within the protocol stack.	3	4
User-space [54]	*Changes to protocol stack:* None. *Changes to existing modules:* Addition of appropriate modules or modification to existing modules, in user-space.	1	1
ECLAIR	*Changes to protocol stack: Protocol stack* may require modification if the required data item is not accessible, as discussed in Chapter 3, Section 3.2. *Changes to existing modules:* For new optimization, (1) new *Protocol Optimizer* is added (PO) or existing PO is modified. For new event, changes required to – (2) *Tuning Layer* (TL) . (3) POs which would be interested in the new event.	2	2

Table 5.6: Portability comparison

Cross Layer Approach	**Portability Analysis**	**Rank**
PMI [34]	Adaptation layers use the operating system APIs. Similarly, guard modules directly monitor data structures within the operating system or use the operating system APIs. For porting to another operating system: (1) Adaptation modules and guard modules will need to be updated to use the new operating system APIs. (2) Guard modules will require modifications to allow it to directly monitor the new operating system data structures.	2
ICMP Messages [73]	The protocol implementation is modified by introducing new control variables and the protocol algorithm is modified for adaptation. For porting to another operating system, the new stack will require modifications: (1) Protocol modifications will need to re-written from scratch. (2) Applications may need modifications if the operating system API for the application changes. (3) ICMP message handler checks the socket data structure. Thus it would need to be re-written since the socket data structure implementation would be different in the new operating system.	3
MobileMan [21]	The protocols are replaced with new Network Status aware protocols. For the new operating system, the protocol implementations will have to re-written from scratch.	3
CLASS [79]	Protocol implementations are modified to allow interaction with other protocols in other layers. For the new operating system, the protocol implementations will have to re-written from scratch.	3
ISP [81]	Protocol implementations are modified to enable embedding of cross layer information in packet headers, parsing such information and adaptations. For the new operating system, implementations will need to be re-written from scratch.	3
User-space [54]	User-space modules would require modifications to the extent of change in the operating system APIs.	2
ECLAIR	Tuning Layers (TLs) provide *generic* and *implementation specific* APIs. For the new operating system, additional *implementation specific APIs* need to be added to the TL. Thus, only Tuning Layer needs to be updated to allow interaction with the new operating system.	1

Above we qualitatively evaluated the efficiency and maintainability of ECLAIR as compared to other cross layer feedback approaches. Next, we present a summary of the qualitative evaluation.

5.2.3 Qualitative Evaluation Summary

The summary is shown in Table 5.7. The table also includes information whether an architecture supports any-to-any layer communication.

Key observations:
The results shows that ECLAIR is useful when a balance between *efficiency* and *maintainability* is required. The qualitative evaluation shows that ECLAIR trades-off efficiency for enhancing maintainability. Since ECLAIR components are outside the stack, its efficiency is lower as compared to architectures (example ISP [81]) which implement cross layer feedback within the protocol stack. However, due to this ECLAIR maintainability is higher. Table 5.8 presents a summary of the key advantages and limitations of the various cross layer approaches.

Appropriateness of an architecture would depend on the requirements for cross layer feedback. In Chapter 7 we present a simple technique for cross layer architecture selection based on the deployment requirements.

Table 5.7: Comparison of cross layer architectures: Summary

Architecture	**Efficiency**				**Maintainability**			**Any-Any layer**
	Time overhead	Space overhead	User-Kernel crossing	Data path delay	Rapid prototyping	Degree of intrusion	Portability	
PMI [34]	4	3	3	1	2	1	2	No
ICMP Messages[73]	5	5	2	2	4	3	3	No
MobileMan [21]	2	2	2	3	4	4	3	Yes
CLASS [79]	2	2	2	3	5	4	3	Yes
ISP [81]	1	1	1	4	3	4	3	No
User-space [54]	2	3	3	3	1	1	2	No
ECLAIR	3	4	2	1	2	2	1	Yes

Table 5.8: Cross Layer Architectures: Summary observations

Cross Layer Approach	**Key Advantages**	**Key Limitations**
PMI [34]	Adaptation is from outside the stack. Hence it has low data path delay and low degree of intrusion.	Event propagates through each adaptation module at a layer. Hence time overhead is high.
ICMP Messages [73]	The cross layer adaptation modules are within the kernel. Hence user kernel crossing overhead is low.	Cross layer optimizations are built into the protocol stack. This leads to high time and space overheads.
MobileMan [21]	All the network event information is available in a single Network Status component. Thus time overhead is low.	Existing protocols have to be replaced to make them Network Status aware. Thus results in poor maintainability and high data path delay.
CLASS [79]	Protocols directly interact with other protocols for cross layer feedback. Due to this, the time overhead is low.	The protocol stack is modified to enable protocol interactions. Thus, the maintainability is poor and data path delay is high.
ISP [81]	Cross layer information is embedded with the packet header. Protocol adaptation is built into the protocol. Hence, the time overhead is low.	Protocol stack has to be modified to introduce adaptations and feedback. This results in poor maintainability and high data path delay.
User-space [54]	All adaptation modules are implemented in user-space. Operating system APIs are used for adaptation. Thus, maintainability is high.	Event and adaptation information has to repeatedly cross the user-kernel boundary. Hence, the efficiency is low.
ECLAIR	Adaptation is from outside the stack. Generic and implementation specific APIs are provided for protocol adaptation. Due to this, the portability is high.	Multiple modules are created for monitoring and adaptation which interact through APIs. This results in high time overhead.

In the next section, we use Receiver Window Control (RWC) (see Section 4.1) as an illustrative example, for a quantitative evaluation of the efficiency of ECLAIR. We compare the ECLAIR and user-space implementations of RWC.

5.3 Quantitative Efficiency Evaluation for RWC

To understand the RWC implementation clearly we first carry out the functional analysis of the ECLAIR (Chapter 4) and user-space [54] implementations. We use the standard software engineering design techniques like *structure chart* and *sequence diagram* [36] for our analysis. Besides structure chart and sequence diagrams, for ease of understanding

cross layer feedback implementation aspects, we propose a notation for the protocol stack and cross layer feedback below.

5.3.1 Cross Layer Feedback Notation

Figure 5.1 depicts our notation for a protocol and a protocol stack. Figure 5.1(a) shows the notation for a protocol implementation within a layer. Each protocol is made up of *algorithms* (for example, congestion control algorithm, etc in TCP), *control data structures* (that is, data structures which contain information about the state of the layer), *protocol data unit (PDU) buffers* (that is, the data which is worked upon by the layer). *Data path* is the sequence of functions within the protocol stack which are concerned only with sending and/or receiving packets. In Figure 5.1, notation for a protocol is as follows:

- Protocol's set of algorithms is denoted by a circle.
- Control data structure (cds) is denoted by a rectangle with rounded corners. Control data structures used by an algorithm are shown attached to the algorithm by a fine dotted line.
- Protocol data unit buffer (pbuf) is denoted by an open rectangle with sharp corners.

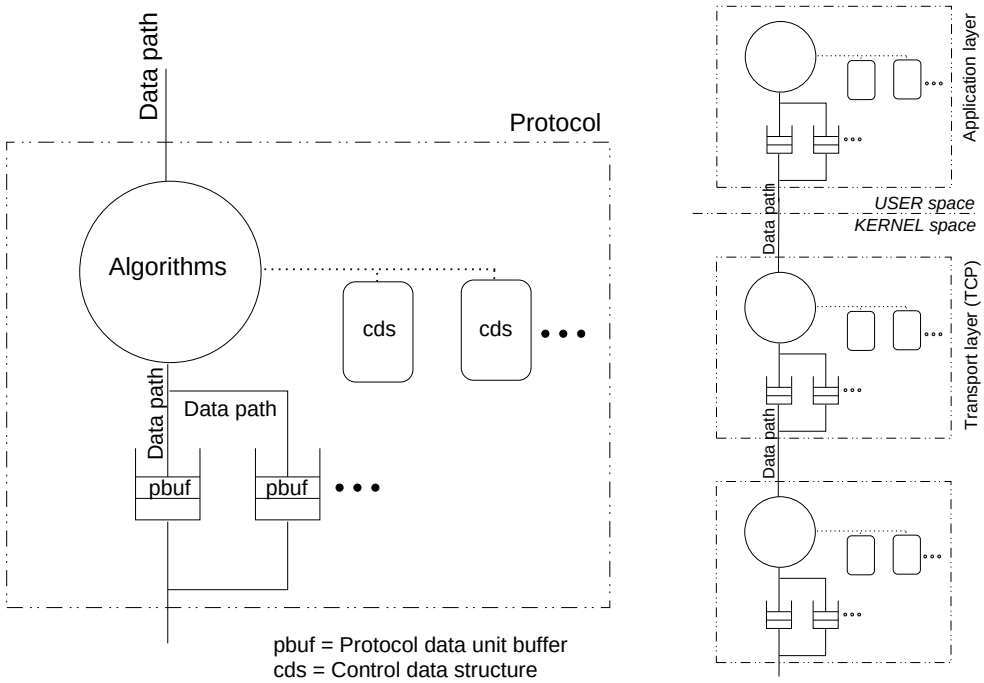
For the stack:

- Stack processing path or data path is shown by a solid line from the algorithms at a layer to algorithms at an adjacent layer (see figure 5.1(b)). The data path passes through a protocol data unit buffer.

Figure 5.1(b) shows the protocol stack made up of multiple stacked protocols. *User-space* implies the memory which is accessible to user programs and *kernel-space* is the memory for the kernel.
Cross Layer Notation Limitations: Our notation for cross layer feedback only provides an overview of the implementation. The notation does not show the exact data structures of a protocol. Also, the notation does not depict the mechanism for interaction of components within the kernel or across user-kernel space.

5.3.2 ECLAIR and User-space: RWC Comparison

Figure 5.2 shows the implementation approach for RWC and ECLAIR. The dotted line with a hollow arrow head represents a read of values from a data structure or another module. The solid line with a solid arrow head represents a write or update of values in a data structure. Read arrows which cross the user-kernel line represent data passing between user and kernel space.



(a) Single protocol implementation (b) Protocol stack

Figure 5.1: Protocol stack schematic

RWC Implementation Overview

Figure 5.2(a) depicts the implementation overview for the approach proposed in reference [54]. It can be seen that, the user-space RWC module is on the data path. Further, user-kernel crossing would be required for updating TCP control data structures.

Figure 5.2(b) shows the ECLAIR implementation. It can be seen that in case of ECLAIR, the RWC module is not on the data path. Further, user-kernel crossing is required only when the application information is to be passed to the RWC module.

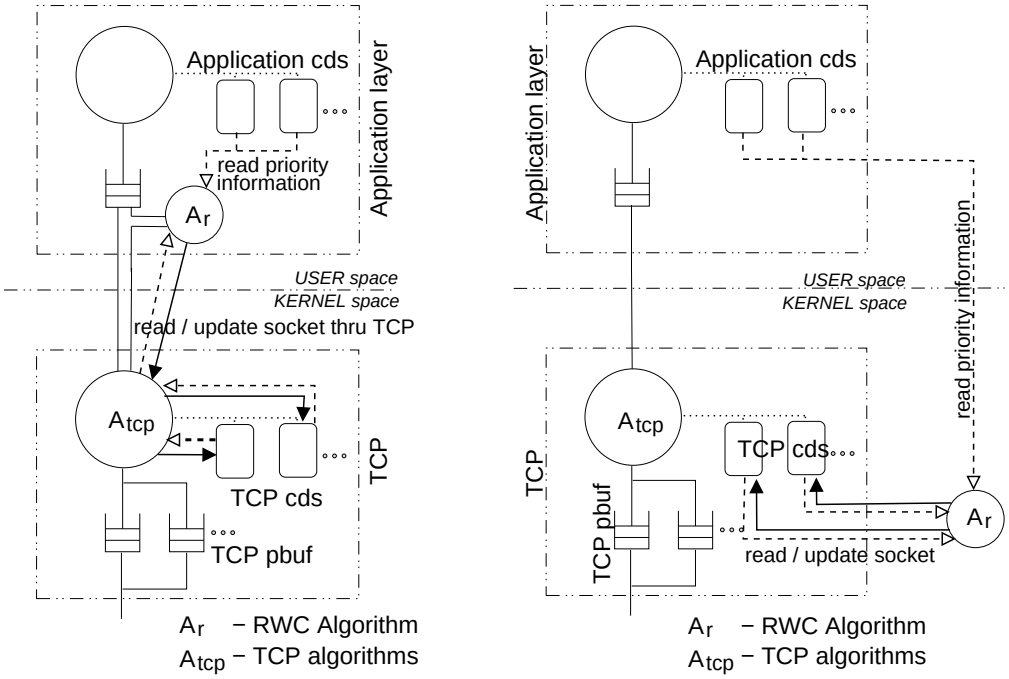
Functional Analysis

User-space implementation:

Figure 5.3 shows the structure chart for the user-space implementation of RWC. The arced arrow shows that the RWC module is invoked repeatedly. In the user-space implementation [54] applications *register* with the RWC module. This RWC *module* is invoked on every `read()` by the registered applications. To modify the receiver window values, the operating system function calls `getsockopt()` and `setsockopt()` are invoked within `read()`. This is implemented by overriding standard C library (libc) functions `read()` and `connect()`, through a new user defined library [54].

ECLAIR:

Figure 5.4 shows the structure chart for the ECLAIR implementation of RWC. The arced arrow shows that the RWC module is invoked repeatedly. In the ECLAIR implementation,



(a) User-space implementation (b) ECLAIR implementation

Figure 5.2: Receiver Window Control implementation

the application *registers* for RWC and passes the required parameters to the RWC module. This is the only time when user-kernel crossing occurs. RWC is invoked at regular intervals by a timer within the kernel. The tuning layer has access to the TCP data structures and updates the receiver window values directly.

Time overhead

From Figure 5.3 it can be deduced that, time overhead for the user-space implementation [54] is

$$O(m \times n) \tag{5.1}$$

where n is the number of applications and m is the number of `read()` calls per application. Besides the execution time of the RWC module, the time overhead may increase further due to the operating system calls that are invoked e.g. `getsockopt()`, `tcp_getsockopt()`, etc. This increase would depend on the implementation of these system calls in the operating system.

In case of ECLAIR, the time overhead is

$$O(t \times n) \tag{5.2}$$

where n is the number of applications and t is the number of times the RWC algorithm is invoked by the timer.

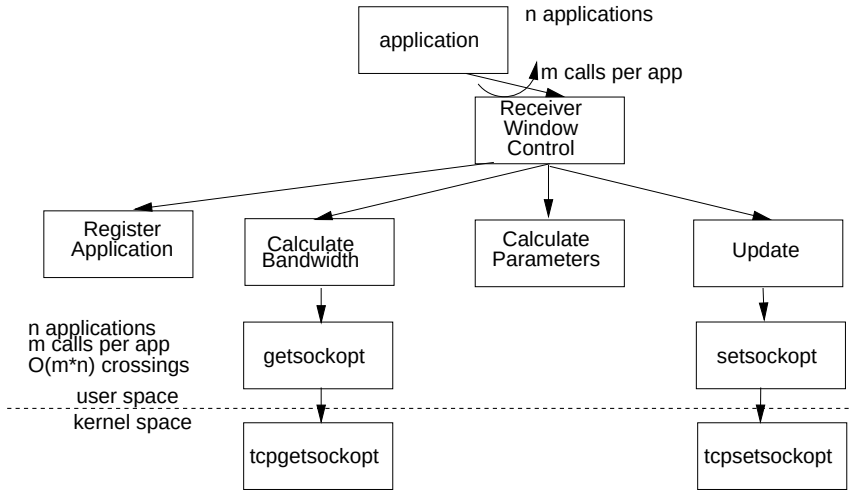


Figure 5.3: Receiver Window Control: Structure chart – user-space

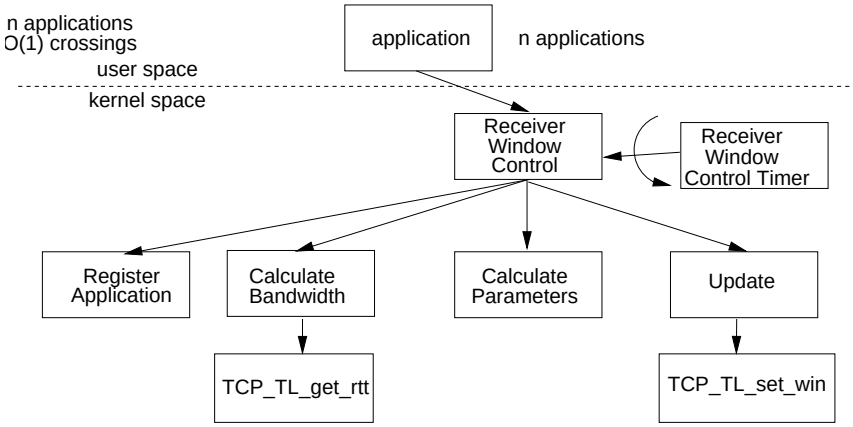


Figure 5.4: Receiver Window Control: Structure chart – ECLAIR

Space overhead

The runtime space overhead of user-space implementation [54] is

$$O(n) \tag{5.3}$$

This is the memory required for storing information about the registered applications.

The runtime space overhead for the ECLAIR implementation is the same as that of user-space, that is

$$O(n) \tag{5.4}$$

This is the space required for registering application information.

User Kernel Crossing

In case of user-space implementation [54], since the RWC module is invoked on each read from user-space, it is evident from Figure 5.3 and 5.2(a) that the user-kernel crossing is

$$O(m \times n) \tag{5.5}$$

where, n is the number of applications and m is the number of *reads* per application.

In case of ECLAIR, all the application information can be passed to the RWC module in a single user-kernel crossing. Thus from Figure 5.4 and Figure 5.2(b) we can deduce that the user-kernel crossing for ECLAIR is:

$$O(1) \tag{5.6}$$

We assume that the number of modules in the structure chart is a measure of the static memory footprint. Based on this measure, the static memory footprint of ECLAIR seems to be higher than that for user-space implementation[54]. This is because the TLs also need to be implemented. Whereas in the case of user-space implementation, existing operating system function calls are used.

To gain an insight into the data path delay, we present sequence diagrams of the implementations in the next section.

Data-path Delay

Data send and receive in protocol stack:
To understand the concept of data path delay, we first present the sequence diagram of send and receive data paths of an *unmodified* protocol stack in Figure 5.5. The sequence diagram shows the sequence of function calls between the various entities in the protocol stack. Figure 5.5 shows how an application sends and receives data, using TCP/IP. For sending, the application invokes `send()` on the socket. In turn the `send()` of TCP then IP is invoked. Finally, the packet is sent out on the network. While receiving the data, the application issues a `read()` call on the socket, which issues a `read()` on TCP. Whenever data is received from IP, it is delivered to the application. This is shown as `data` over the dotted arrows.
Data send and receive: user-space RWC
In case of user-space implementation [54], RWC is built into the `read()` of the application. Figure 5.6(a) shows the modified data path for the user-space implementation. The `data-a` return shows the actual return path if `read()` was not modified. It can be seen from the figure that the data return from the modified `read()` is delayed till the RWC algorithm completes its run. This is the data path delay. Considering all the *registered*

applications together, excluding other overheads, the overall data path delay (Figure 5.3) is

$$O(m \times n) \tag{5.7}$$

Data send and receive: ECLAIR RWC
Figure 5.6(b) shows the data path for the ECLAIR implementation of receiver window control. The ECLAIR implementation is not on the data path and hence does not impact the data path of the application.

Other limitations of user-space mechanism

Most operating systems provide APIs for applications, such as `getsockopt()` and `setsockopt()`, to read and update the socket parameters. However, the manipulation of protocol parameters is restricted to what is permitted by the operating system. For example, `setsockopt()`, which internally calls `tcp_setsockopt()`, allows changes to a limited set of TCP parameters. `tcp_setsockopt()` allows update to `window_clamp` in the TCP control data structure. However, in case of Receiver Window Control, the value of `rcv_ssthresh` was also to be updated. This was not possible through `setsockopt()`. Further, our trails show that reducing `window_clamp` does not have an effect on an active session. This has also been stated in reference [78]. Similarly, `getsockopt()` cannot read the values of certain TCP parameters individually. For example, for reading the state of a TCP connection, an `info` structure (which has many other parameters also) is used.

In summary, some of the operating system APIs, that enable interaction with the stack, may not provide the flexibility required for implementing a cross layer feedback system. Moreover, the APIs restrict the usage to user level programs, which would impact the efficiency of a cross layer implementation. There would be an additional efficiency penalty due to repeated user-kernel crossing. See Section 5.1.1 for user-kernel crossing metric.

In this section we compared the user-space and ECLAIR implementations of RWC. Through analysis we showed that ECLAIR is an efficient architecture for RWC type of cross layer feedback.

5.3.3 Quantitative Evaluation Summary

Table 5.9 shows the quantitative evaluation summary of ECLAIR and user-space implementations of receiver window control. (see equations (5.1) - (5.7)). Both have similar level of maintainability and minimum intrusion. Portability of the ECLAIR implementation is higher, because of the TLs. In the next section we measure ECLAIR overheads.

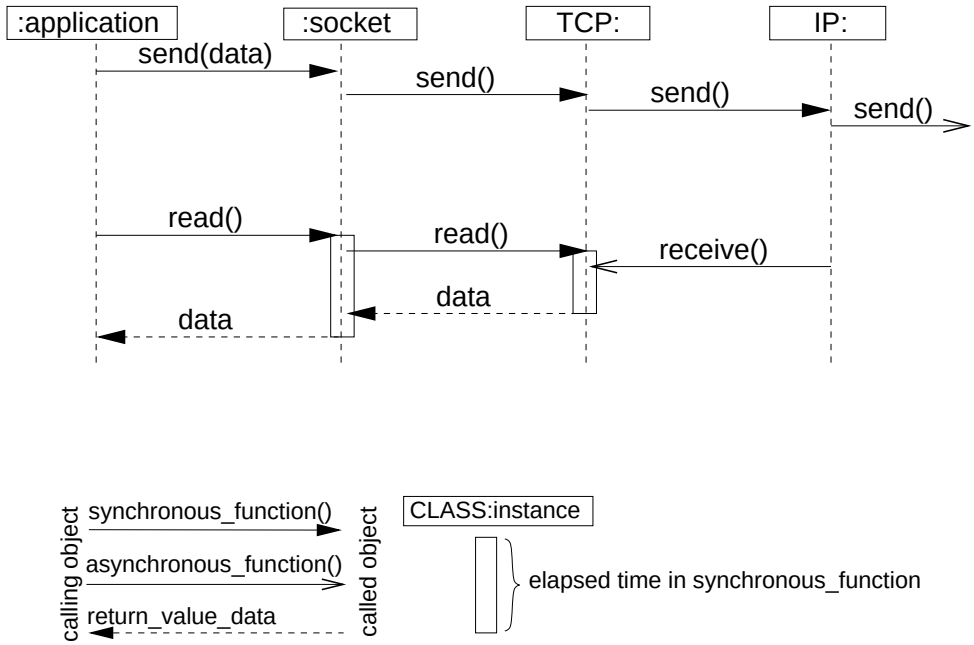


Figure 5.5: Sequence diagram of data send and receive paths for an unmodified protocol stack

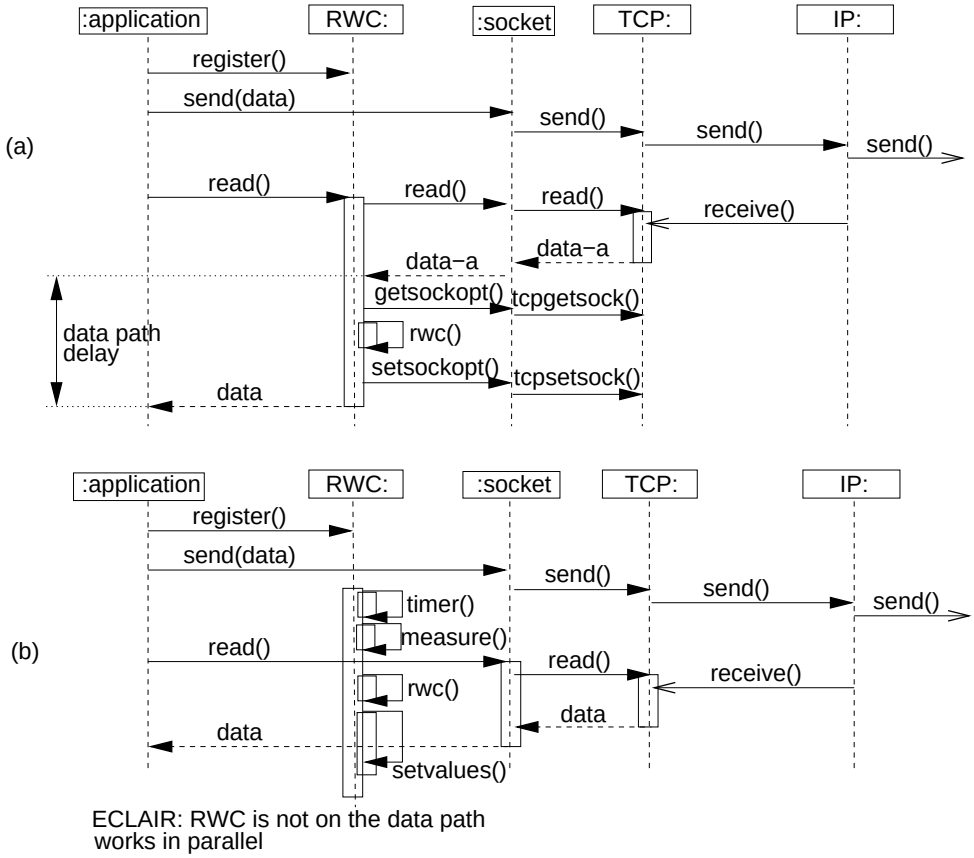


Figure 5.6: Data send and receive with RWC: (a) user-space (b) ECLAIR

Table 5.9: ECLAIR and user-space quantitative comparison summary

Evaluation metric	**ECLAIR**	**user-space**	**Description**
Time overhead (complexity)	$O(t \times n)$	$O(n \times m)$	n = number of applications t = number of invocations of RWC (ECLAIR) m = number of invocations of RWC per application (user-space)
Space overhead (complexity, footprint)	complexity: $O(n)$, footprint: higher initially	complexity: $O(n)$, footprint: lower	Space complexity: Space required for information about registered applications footprint: static space required for executables
User-kernel crossing	$O(1)$	$O(n \times m)$	ECLAIR: time required for passing user parameters to kernel using `ioctl()` user-space: time required for `getsockopt()` and `tcp_getsockopt()`
Data path delay	-	$O(n \times m)$	(same as above)

n is the number of applications,
m is the number of reads per application in user-space case,
t is the number of times the RWC algorithm is invoked in ECLAIR

5.4 ECLAIR Overhead Measurement

The broad aim of the profiling experiments is to verify that ECLAIR imposes minimal overhead on the operating system. Due to non-availability of the implementation code of existing cross layer approaches (discussed in Section 5.2), profiling of these approaches is not feasible. Hence we compare ECLAIR with the following:

- *Modifying the protocol for cross layer feedback:* This would enable comparison of ECLAIR with all architectures where the cross layer algorithm is built into the data path.

- *Using operating system APIs for cross layer feedback:* This would enable comparison of ECLAIR with architectures which are implemented in user-space and use operating system APIs. Since, ECLAIR is *outside* the stack, it needs to locate the data structure that is to be monitored or updated. This adds to the time overhead. Hence, we also compare ECLAIR efficiency in searching data structures within the protocol stack, to the operating system API efficiency. We use RWC as the example.

- *No modifications to the stack:* This comparison would give us an estimate of ECLAIR impact on data path delay with reference to the case when no cross layer feedback is implemented.

In section 5.1.1 we identified *time overhead*, *space overhead*, *data path delay* and *user kernel crossing* as the metrics for efficiency. The above stated experiments would give us an estimate of ECLAIR performance for user-kernel crossing and data path delay metrics, relative to other approaches. Determining time and space overhead requires implementation of a full cross layer optimization. Hence, we do not focus on the time and space overhead. Next, we describe the profiling tools we experimented with.

5.4.1 Profiling Tools

In Chapter 4, Section 4.1 we presented the design and implementation of Receiver Window Control using ECLAIR. We use that prototype implementation with modifications for profiling ECLAIR.

To measure the data-path delay overhead, measurement of the impact on the time taken for packet movement between the network interface and the socket layer is required. For user-kernel crossing time measurement time-stamps in user and kernel space are required. For data structure search time, a facility for time-stamp before and after search is required. This type of profiling requires a lightweight (imposes minimal run-time overheads on the operating system) profiling tool which can be easily integrated with the operating system's protocol stack.

The following open source tools are suitable for the above measurements, in Linux [99]:

- MAGNET (Monitoring Apparatus for Generic kerNel Event Tracing) [28, 103]. MAGNET was earlier known as MAGNeT (Monitor for Application Generated Network Traffic). This tool is available for download from [103].
- LTT (Linux Trace Toolkit) [87]. This tool is available for download from [102].

MAGNET

MAGNET [28, 103] is a tool that traces packets as they move through the protocol stack. Both packet receipt and packet send are traced. MAGNET requires modification to the operating system stack. *Hooks* (function calls) are placed in the protocol stack. The hooks are placed in link, IP and TCP layers. These hooks call a MAGNET data recording procedure. This recorded data can be accessed by user-space applications.

Figure 5.7 [28] shows on overview of the operation of MAGNET. The application issues `send()` or `recv()` calls for sending or receiving data. Inside the protocol stack, TCP, IP and other protocols are used for data send and receive. `magnet_add()` is called

from within the protocol stack to trace packet movement. `magnet_read()` is used to copy the trace from the kernel buffer to a disk file. MAGNET uses the CPU cycle counter for generating high-resolution time-stamps.

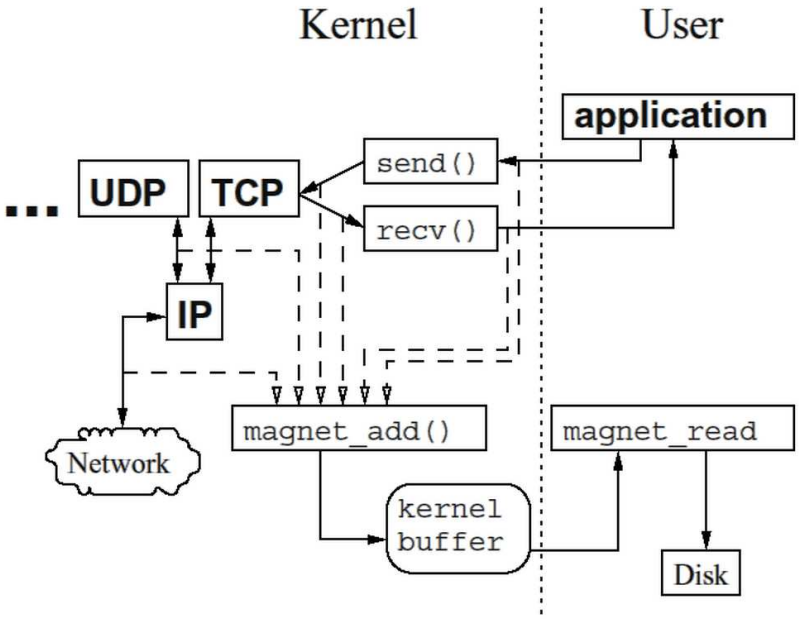


Figure 5.7: MAGNET details [28]

LTT

Linux Trace Toolkit [87, 102] has the following components: *kernel patch* which logs events to be traced, *kernel module* which stores events and interacts with *trace daemon*, trace daemon which reads kernel module's output and stores it on disk, *data decoder* which is used for analysis and converting the trace to human readable form [102]. Figure 5.8 shows LTT architecture.

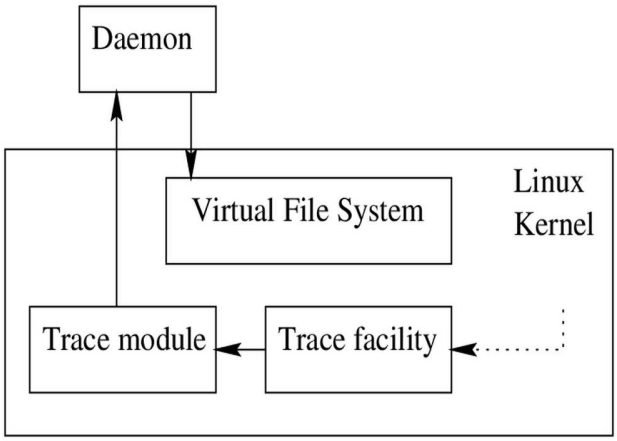


Figure 5.8: LTT details [87]

OProfile

Another tool that we considered was Oprofile [105]. OProfile is a low overhead continuous profiler. It regularly samples the CPU registers. It converts this sampled information into a statistical report about which program was executed how often. We experimented with this tool also (by patching the kernel, recompiling and running a few tests). The tool could provide information about which code segment occupied the CPU for what fraction of time. However, there was no facility to measure the time for packet movement within the stack. Hence, we did not use this tool.

5.4.2 Instrumenting the Linux kernel

Both the profiling tools MAGNET [28, 103] and LTT [87, 102] provide Linux kernel *patches* for updating the kernel source code, to enable kernel profiling. Hence we patched the Linux 2.4.19 kernel with both the tools. We used the 2.4.19 kernel since this was supported by both the tools. The kernel source code is available at the Linux kernel source site [101] and the IIT-Bombay mirror site [100]. The patch installation required some manual editing of kernel source files. This was required since the patches of both the tools updated some common files at similar locations. Hence, the patch which was installed second failed at some points.

Only MAGNET used: We intended to use both the profiling tools since we required features of both the tools. For data-path delay profiling we required the facility to trace packet movement within the stack. We also wanted to trace the start and end of RWC invocation.

MAGNET provides the feature of tracing packet movement within the stack and LTT allows creation of user defined events in kernel modules and user programs. However, LTT cannot trace a packet's movement within the stack, although it provides events related to packets crossing the network and socket layers. This combination would have enabled us to do the required tracing. However, during our experiments we noticed that the LTT overheads significantly skewed the readings for data-path delay. We noticed this because of the occasional but *extremely* large values of data-path delay. We confirmed this by measuring data-path delay with and without LTT. We ran our full set of experiments, discussed in Section 5.4.4. Finally, we decided to use MAGNET only for the purpose of profiling. Due to this it was not possible to trace RWC start and end. However, this would not affect the quality of the results, since the primary aim was to study the effect of ECLAIR on data-path delay.

Instrumenting for user-kernel crossing: MAGNET does not provide a facility for creating and tracing events within an application. For user-kernel crossing we needed a time-stamp before invocation of a system call in user-space, and after completion of the

call in kernel-space. For this instrumentation we manually modified the kernel. Initially, we placed the system call `do_gettimeofday()` in TCP to get and print the time-stamp. During the initial set of runs we noticed that the time measurement granularity (microseconds) available in kernel 2.4.x was not sufficient since the operations that we intended to measure (data structure search), were taking less than 1 μsec. Hence, for higher accuracy, we captured the CPU cycles. We used the function `get_cycles()` available in the kernel include file `asm/timex.h`. To get the CPU cycles in user-space, we used `get_cycles()` in the test-application and compiled it with the kernel include file `asm/timex.h`. Its prototype is

```
#include <linux/timex.h>
cycles_t get_cycles(void);
```

The Linux `get_cycles()` function is used to get timestamps with very low overhead. CONFIG_X86_TSC has to be defined during kernel compilation time, else `get_cycles()` returns 0. Internally, `get_cycles` uses the function `rdtsc` (Read Timestamp Counter) for reading the timestamp counter (TSC). The time for reading of TSC is extremely small (ten instruction times) compared to the time interval being measured (thousands). Hence, we have not done any corrections to the measured time, to account for cycles taken to read the values from the register.

5.4.3 Design of Experiments

The aim of the experiments was to compare ECLAIR overheads with that of other approaches. We conducted two sets of experiments to

- measure the impact on data path delay
- measure the data structure search time and user-kernel crossing time

For data path delay measurement, simulation of cross layer overhead was required during some stack activity. For the stack activity we initiated a download from a website.

Overhead simulation

To simulate cross layer feedback execution we executed an empty loop within the kernel. To simulate an increased load we increased the number of loop executions. While executing the download, we ran the empty loop for 2×10^5, 5×10^5, 10×10^5, 15×10^5 and 20×10^5 cycles.

ECLAIR overhead simulation

In case of ECLAIR we executed the empty loop within the RWC PO. When the PO received an input from the user, it executed the empty loop. A kernel timer [13] within the PO controlled the repetition of the loop at regular intervals. We varied this interval to simulate the effect of repeated execution of ECLAIR. The PO module was removed from the kernel on completion of an experiment run. This stopped the loop executions.

Protocol modification simulation

To simulate this we modified the `tcp_v4_rcv()` function in TCP (`tcp_ipv4.c`). We introduced an empty loop in this TCP function. This simulated a *load* on the data path. Whenever a packet was received this loop was executed in the `tcp_v4_rcv()` function. Next, we present the experiment setup and results.

5.4.4 Experiment Setup and Results

We ran the experiments on a desktop with the configuration - Intel Pentium4 CPU, 1.90GHz, 256 MB RAM, 256KB cache.
Custom kernels for experimentation:
We compiled separate kernels patched with MAGNET to measure the impact on data path delay. In one of the kernels we modified TCP to introduce the empty loop. We refer to this as the *TCP-MAGNET* kernel. In the other kernel we did not modify TCP. We used this kernel for ECLAIR measurements and measurement of packet movement when no cross layer feedback is implemented. We refer to this kernel as the *MAGNET-only* kernel.

Experiment 1: Impact on data path delay

In this experiment we measured the time taken by a packet to traverse up the stack (from network interface to the socket layer). This is the data path time, when any data is being downloaded onto the device. We also measured the time taken by the acknowledgments generated at TCP layer to traverse from TCP to the network interface layer. This is the data path time for packets being sent out from the device.

We ran *wget* [107] to download a file from a remote website (`www.kernel.org`) [101]. A single connection was created. `magnet_read` [28, 103] was started in the background, to trace packet movement through the stack.

- We ran this experiment on both the TCP-MAGNET and MAGNET-only kernels.
  - In the MAGNET-only kernel we ran ECLAIR to simulate cross layer load. We invoked ECLAIR at different frequencies of 10, 13, 20, 33 and 100 times per

second. 100 per second is the maximum possible invoke frequency using kernel timers in a 2.4.x kernel.

  - In case of TCP-MAGNET kernel, the load was built into TCP layer, as explained above.

- We also used the MAGNET-only kernel to get a measurement of the packet movement within the stack, when no cross layer feedback is running.

- We repeated each experiment 10 times

  - for each *load*, on the TCP-MAGNET kernel
  - for each load and for each *invoke frequency* – for ECLAIR measurements, in the MAGNET-only kernel
  - without any load to get a measurement for no cross layer feedback, in the MAGNET-only kernel.

- To check the impact of packet arrival rate also on the data path delay, we selected two kernel source mirrors for file download, one offering a high throughput and another lower and repeated the above experiments for each packet rate.

Analysis of Experiment 1

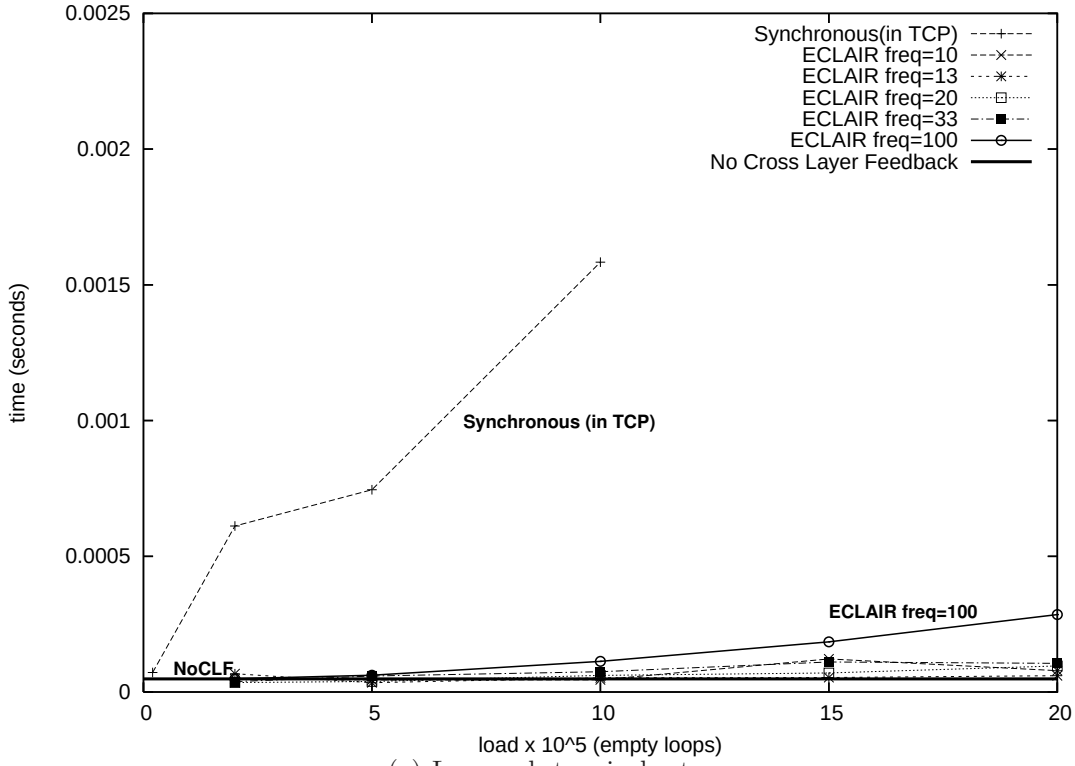
Figure 5.9(a) shows the results for low packet rate. Figure 5.9(b) shows the result for high packet rate.

Tables 5.10 and 5.11 show the mean and standard deviation values for low and high packet rate, respectively.

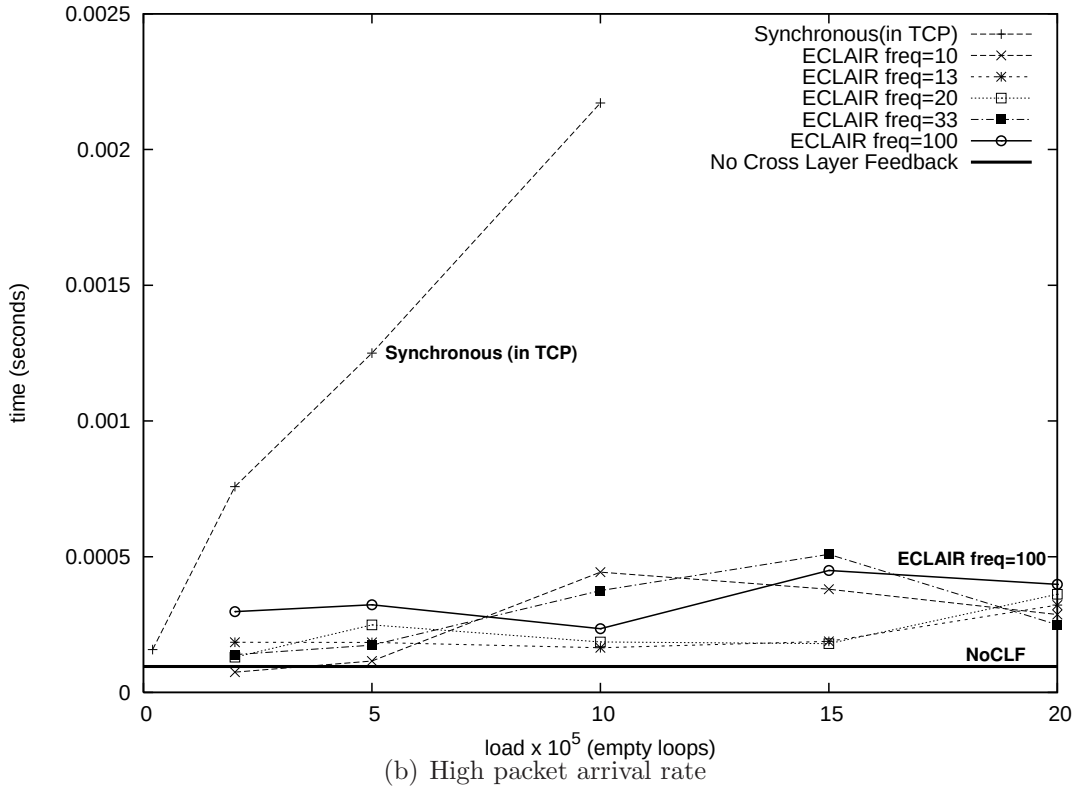
TCP-MAGNET kernel: for this case, since the cross layer load (empty loop) is executed for every packet, the data path delay is high. Further, the data path delay increases almost linearly with the increase in cross layer load. Compared to no cross layer feedback, the data path delay in case of TCP-MAGNET kernel is higher by approximately 49% for low load (2×10^5) and approximately 30 times higher at high load (10×10^5).

MAGNET-only with ECLAIR kernel: for this case, the load execution is controlled by a timer. Compared to no cross layer feedback, the data path delay in case of ECLAIR is higher by approximately 19% in case of low load (2×10^5) and low invocation frequency (10 times per second). In case of high load (20×10^5) and high invoke frequency (100 times per second), the data path delay is approximately 6 times higher.

Result: This above results show that, ECLAIR's impact on data path is much lower than the case of implementing cross layer feedback within the protocol itself.



(a) Low packet arrival rate



(b) High packet arrival rate

Figure 5.9: Data path delay comparison: ECLAIR v/s TCP modification

Table 5.10: Data path delay: Mean and standard deviation for low packet rate

Invoke frequency (per second)	Load $\times 10^5$	$\bar{X} \times 10^{-5}$ (seconds)	$\sigma \times 10^{-5}$ (*seconds*)
No CLF		4.810 ± 1.171	19·847
10	2	4.903 ± 1.859	30·417
	5	4.411 ± 1.103	18·507
	10	4.506 ± 0.689	11·674
	15	12.161 ± 8.625	143·541
	20	7.884 ± 3.245	49·442
13	2	6.756 ± 3.076	51·198
	5	3.440 ± 0.175	2·956
	10	5.249 ± 1.684	28·147
	15	5.354 ± 0.854	14·326
	20	6.023 ± 1.634	26·828
20	2	3.489 ± 0.129	2·146
	5	3.882 ± 0.749	12·543
	10	6.093 ± 1.849	30·815
	15	7.038 ± 1.994	33·394
	20	9.630 ± 3.044	50·453
33	2	3.845 ± 1.067	16·908
	5	5.878 ± 3.053	47·806
	10	7.478 ± 2.384	40·349
	15	11.056 ± 3.320	54·697
	20	10.585 ± 1.916	31·925
100	2	4.905 ± 2.494	41·821
	5	6.179 ± 1.541	25·148
	10	11.309 ± 1.757	29·629
	15	18.495 ± 2.676	44·471
	20	28.501 ± 3.417	56·278
Synchronous (in TCP)	0.2	7.164 ± 2.853	48·296
	2	61.179 ± 39.668	699·929
	5	74.501 ± 4.334	72·778
	10	158.373 ± 6.292	105·015

Table 5.11: Data path delay: Mean and standard deviation for high packet rate

Invoke frequency (per second)	Load $\times 10^5$	$\bar{X} \times 10^{-5}$ (seconds)	$\sigma \times 10^{-5}$ (*seconds*)
No CLF		9.549 ± 4.406	152·759
10	2	7.486 ± 3.939	118·642
	5	11.542 ± 5.181	168·092
	10	44.305 ± 18.059	579·235
	15	38.024 ± 19.379	625·805
	20	28.674 ± 10.518	345·489
13	2	18.468 ± 8.868	285·295
	5	18.436 ± 8.301	265·439
	10	16.443 ± 6.980	225·76
	15	18.798 ± 7.506	242·977
	20	32.203 ± 15.980	523·711
20	2	12.966 ± 5.132	164·567
	5	24.851 ± 11.472	367·199
	10	18.599 ± 10.680	343·186
	15	17.993 ± 8.038	259·836
	20	36.171 ± 16.270	537·46
33	2	13.912 ± 6.766	219·902
	5	17.429 ± 8.934	287·137
	10	37.503 ± 17.780	571·269
	15	50.871 ± 21.883	731·215
	20	24.931 ± 11.905	399·365
100	2	29.779 ± 12.380	336·842
	5	32.297 ± 13.281	428·941
	10	23.471 ± 8.824	282·737
	15	44.926 ± 18.624	601·483
	20	39.796 ± 9.016	299·111
Synchronous (in TCP)	0.2	15.792 ± 10.137	318·303
	2	75.832 ± 13.294	501·423
	5	125.026 ± 9.725	338·057
	10	217.152 ± 10.074	351·64

Experiment 2: Data structure search time and user-kernel crossing

In this experiment, we measure the time take by the RWC PO to search for TCP sockets. This includes the time for user kernel crossing. We compare this with the time taken by an operating system API to locate the data structure. We used `setsockopt()` system call to update the TCP data structure.

Operating system API search:
The start of the search time is captured just before the API call. In case of TCP sockets, the `setsockopt()` system call flow terminates at the function `tcp_setsockopt()`. We added code within this function to measure the elapsed CPU cycles when this function is entered. This is the end time of search.

ECLAIR search:
In case of ECLAIR, we captured the CPU cycles before the user invoked RWC and after the socket was located by the RWC PO. The RWC PO does not use any system calls for locating the PO. For efficient search we implemented the `tcp_hashfn()`, from `tcp_ipv4.c` file, in the RWC PO. This function was used to located the TCP *hash bucket* in which the socket is located. Once the hash bucket was located, the exact socket was located by traversing the socket linked list. Since a linked list traversal was involved, we also studied the impact of the length of the list, that is, the *depth* of the hash bucket. As discussed in Section 5.3, in ECLAIR the user parameters can be passed to the RWC PO in a single user-kernel crossing. We used an array to pass the socket information to the PO and measured the impact on socket search.

Creating sockets:
We used a modified version of a socket client from the book – Unix Network Programming [71]. For controlling the depth of the TCP hash bucket, we created an array of port numbers which would hash into the same bucket. For this, we created a script which first tested the port numbers which hash into the same bucket. The server side port number and address were fixed (our department's web server). The client side address was fixed, that is, our test machine. The test program used these parameters – server address, server port and client address. The client port was varied to determine the *colliding* ports. These port numbers were captured into a two-dimensional array. Each array row had 8 port numbers which hashed into the same hash bucket.

For the script that ran the experiment, the first parameter was the number of sockets required per bucket (1 to 8). The next parameter was a multiplier (1 to 5). Thus, when sockets per bucket was 1, the total sockets created were 1 to 5. When the sockets per bucket were 2, the sockets created were 2, 4, 6, 8, 10. Finally, the sockets created were a multiple of 8, that is, from 8 to 40. Each run was repeated 10 times. The results show values averaged across the runs.

Effect of CPU cache:
During the experiments we noted that the CPU cache affected the search time, as the number of sockets were increased. Thus, to study the impact of caching on search time we carried out two sets of experiments. One with caching allowed and another with the cache invalidated. We were unable to disable the cache through the BIOS settings, hence we invalidated the cache by updating the values in a large `int` array (size 500,000) , using a `for` loop. This loop was called before each run in the application before invoking the operating system API and inside the ECLAIR PO.

Analysis of Experiment 2

The experiment results are shown in Figures 5.10(a) to 5.10(d). The mean and standard deviation values are shown in Tables 5.12 to 5.15.

1. *Scenario 1 (Figure 5.10(a)): No array used; CPU caching allowed:*

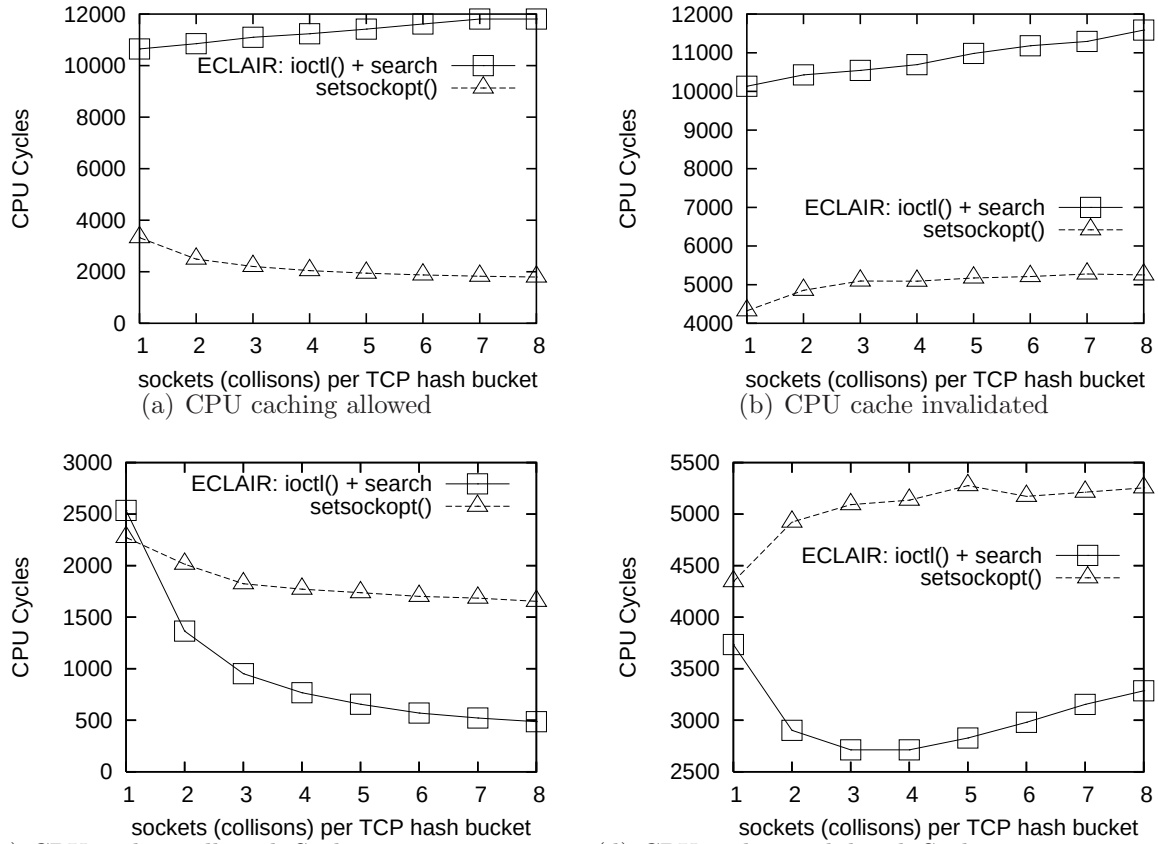
   - *setsockopt:* The search time per socket decreases as the hash bucket depth increases. This decrease can be attributed to the CPU cache.
   - *ECLAIR:* The search time per socket increases as the socket depth increases. This is because the RWC PO needs to travel the linked list of sockets in the hash bucket. An increased depth means a longer linked list and hence more time is needed by ECLAIR. The time taken by ECLAIR is approximately 7 times higher than setsockopt when the bucket depth is 8.

2. *Scenario 2 (Figure 5.10(b)): No array used; CPU cache invalidated:* The cache was invalidated by processing a large array as explained above.

   - *setsockopt:* The search time increases as compared as the bucket depth increases.
   - *ECLAIR:* The search time increases as in the earlier case. In this case the time taken by ECLAIR is approximately 2 times the time taken by setsockopt, for a bucket depth of 8.

3. *Scenario 3 (Figure 5.10(c)): Array used; CPU caching allowed:*

   - *setsockopt:* The array cannot be used for setsockopt, since the system call allows processing of one socket at a time. The result of scenario 1 is repeated here, that is, search time per socket decreases as hash bucket depth increases due to CPU cache.
   - *ECLAIR:* The array leads to a substantial reduction in the time taken for search per socket. This is due to the reduction in the user-kernel crossings.



(a) CPU caching allowed

(b) CPU cache invalidated

(c) CPU caching allowed; Socket information to ECLAIR passed in array

(d) CPU cache invalidated; Socket information to ECLAIR passed in array

Figure 5.10: User-kernel crossing + socket search time: ECLAIR v/s setsockopt()

For example, if there are 5 sockets, then in case no array is used, the user kernel crossing occurs 5 times. While in the case when array is used, the user kernel crossing overhead occurs only once. The time taken by ECLAIR is approximately 11% higher than setsockopt when the bucket depth is 1. However, the time taken by ECLAIR is approximately 71% *lower* when the bucket depth is 8. This is because the user-kernel crossing occurs only once in case of ECLAIR, since an array is used. Note that the values shown for each bucket depth are averaged across a number of sockets. Recall that for each bucket depth multiplying factors of 1, 2, 3, 4 and 5 are used. For example, in case of bucket depth 1, the values are averaged across the number of sockets created, that is, 1, 2, 3, 4 and 5. Similarly, in case the bucket depth is 2, the sockets created are 2, 4, 6, 8, 10. It can be seen that, as the number of sockets increase, due to the use of array the average user-kernel crossing time decreases. Hence, overall time (user-kernel crossing + search) for a bucket depth decreases as the bucket depth increases.

Table 5.12: Mean and standard deviation: No array used; CPU caching allowed

Sockets per bucket	ECLAIR:ioctl+search (CPU cycles)		setsockopt (CPU cycles)	
	$\bar{X}$	σ	$\bar{X}$	σ
1	10655 ± 82	512	2898 ± 289	1809
2	10850 ± 62	549	2242 ± 165	1460
3	11107 ± 58	635	2032 ± 116	1262
4	11285 ± 113	1422	1918 ± 87	1090
5	11426 ± 55	776	1834 ± 70	981
6	11642 ± 51	780	1789 ± 59	910
7	11815 ± 98	1628	1753 ± 50	839
8	11823 ± 52	921	1729 ± 44	791

Table 5.13: Mean and standard deviation: No array used; CPU cache invalidated

Sockets per bucket	ECLAIR:ioctl+search (CPU cycles)		setsockopt (CPU cycles)	
	$\bar{X}$	σ	$\bar{X}$	σ
1	10158 ± 86	537	4633 ± 159	996
2	10456 ± 65	577	5019 ± 93	826
3	10538 ± 58	633	5168 ± 71	773
4	10700 ± 53	667	5156 ± 56	711
5	10946 ± 124	1734	5225 ± 52	732
6	11196 ± 52	799	5268 ± 49	753
7	11315 ± 103	1718	5332 ± 93	1542
8	11525 ± 73	1290	5278 ± 38	680

4. *Scenario 4 (figure 5.10(d)): Array used; CPU cache invalidated:*
   The scenario is similar to the previous one. However, since there is no caching, the time taken for socket search tends to increase as compared to the case with array and cache. In this case the time taken by ECLAIR is 14% lower than setsockopt when the bucket depth is 1 and it is about 37% lower when the bucket depth is 8. In case of ECLAIR, the time required increases after a depth of 5. This is probably due to the increase in time required for traveling the socket linked list at higher bucket depths.

Result: The above experiments show that as the number of sockets increase, by using appropriate design (array for passing information to PO in kernel), ECLAIR architecture shows higher savings in case of user kernel crossing. Further, as the hash bucket depth

Table 5.14: Mean and standard deviation: Array used; CPU caching allowed

Sockets per bucket	ECLAIR:ioctl+search (CPU cycles)		setsockopt (CPU cycles)	
	$\bar{X}$	σ	$\bar{X}$	σ
1	2535 ± 549	3434	2274 ± 181	1133
2	1365 ± 310	2744	2014 ± 121	1069
3	952 ± 212	2296	1824 ± 81	877
4	767 ± 168	2039	1772 ± 66	801
5	656 ± 136	1901	1738 ± 52	736
6	570 ± 112	1726	1702 ± 44	677
7	522 ± 98	1635	1685 ± 39	658
8	486 ± 88	1539	1654 ± 33	583

Table 5.15: Mean and standard deviation: Array used; CPU cache invalidated

Sockets per bucket	ECLAIR:ioctl+search (CPU cycles)		setsockopt (CPU cycles)	
	$\bar{X}$	σ	$\bar{X}$	σ
1	3735 ± 424	2654	4345 ± 145	906
2	2902 ± 247	2184	4922 ± 90	801
3	2713 ± 170	1841	5092 ± 68	745
4	2712 ± 130	1630	5135 ± 61	768
5	2828 ± 106	1487	5277 ± 186	2608
6	2980 ± 94	1440	5173 ± 42	648
7	3153 ± 85	1408	5213 ± 39	649
8	3286 ± 82	1456	5254 ± 41	726

increases beyond 2, ECLAIR shows better performance irrespective of whether caching is enabled or disabled.

5.4.5 ECLAIR Overheads Summary

The key observations from ECLAIR overhead evaluation are as follows:

- ECLAIR has negligible impact on the data path as compared to implementation of cross layer feedback within the protocol stack
- By proper design of ECLAIR modules:
  - ECLAIR's user-kernel crossing time is minimized

  - ECLAIR's data structure search time is:
    * better than an operating system API when the TCP hash-bucket depth is high
    * comparable to using an operating system API when the TCP hash-bucket depth is low

In this section we presented the experiments for measuring ECLAIR overheads. The analysis in earlier sections and the experiments show that ECLAIR is an efficient and easily maintainable cross layer architecture. However, ECLAIR has some limitations which we present in the next section.

5.5 ECLAIR Limitations

The following are some of the limitations of ECLAIR:

- It requires modification to the stack if some data structure is not accessible (see Chapter 3, Section 3.2).
- A Protocol Optimizer (PO) does not directly access a protocol's data structure. A PO uses a Tuning Layer's (TL) API for this. A PO invokes a TL's *generic* API which in turn invokes the *implementation specific* API. Thus, execution overheads are increased due to multiple function calls as compared to direct access to protocol data structures by the PO.
- ECLAIR modules are not embedded within the existing protocol stack code. Thus, ECLAIR cannot support per packet adaptation. This is discussed further in Chapter 7. See Chapter 2, Section 2.5.1 for a discussion on adaptation types.
- It does not provide a direct solution to solve cross layer feedback conflicts and dependency cycles [41].
- It does not provide a direct solution to ensure protocol correctness in presence of cross layer feedback.
- ECLAIR requires super user privileges for implementation.

However, these are not major limitations. This is due to the following: (1) only minor modifications are required to the stack to enable access to data structures. (2) The function call overheads are not significant since, they would form a small fraction of the total overheads of the cross layer system. (3) ECLAIR does not restrict introduction of additional mechanisms for per packet adaptation. Thus other architectures can co-exist with

ECLAIR to enable per packet adaptation. (4) Issues such as impact on protocol correctness, cross layer feedback conflict and dependency cycles [41] are intrinsic to cross layer feedback. These issues would thus exist, irrespective of the architecture used. Although ECLAIR does not provide a direct solution to these issues, its components (TLs and POs) can be extended to address these issues. (5) Cross layer system implementers would have access to the operating system internals and would have super users privileges. Further, the super user constraint restricts uncontrolled cross layer modifications to the protocol stack. Next, we discuss some security issues which could be applicable to ECLAIR.

5.6 Security Issues

ECLAIR requires super user privileges for implementation, since ECLAIR components reside in the kernel. However, introducing these additional components may make the kernel vulnerable to malicious attacks. Thus, kernel protection is essential. Reference [83] provides details on how to prevent malicious code attacks launched through loadable kernel modules. Below we present examples of the security mechanisms which may be required.

If ECLAIR on the device allows interaction with other components in the network, it may be possible to send data to the device with the intent of decreasing the device performance or throughput. Thus, an authentication mechanism may be required between ECLAIR components within the device and those on the network.

In addition, it may be possible to replace ECLAIR components with malicious components, which may impact the device behaviour. Thus a certification or signing mechanism may be required to ensure that only signed and certified components are installed on the device. The details about the security mechanisms to ensure device safety is beyond the scope of this thesis.

5.7 Summary

In this chapter we selected the performance metrics for evaluating any cross layer feedback architecture. We identified the following metrics: (1) time overhead, space overhead, user kernel crossing and data-path delay for *efficiency* (2) rapid prototyping effort (changes required to the stack and cross layer optimization for adding a new cross layer optimization), degree of intrusion (changes required to the stack for introducing cross layer feedback) and portability effort (changes required to the cross layer optimization for porting to another system) for *maintainability*.

We compared ECLAIR with other cross layer feedback mechanisms. The comparison highlights the efficiency and maintainability benefits of ECLAIR. We also compared the

ECLAIR and user-space implementations of receiver window control. Our evaluation shows the benefits of using ECLAIR for asynchronous type of protocol optimizations. Our experimental results verify and the highlight the benefits of ECLAIR.

We present a detailed design guide for ECLAIR in Chapter 7. In the next chapter we propose improvements to ECLAIR, which would help maximize the benefits of cross layer feedback using ECLAIR.

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If you optimize everything, you will always be unhappy
- Donald Knuth

Chapter 6

ECLAIR Optimizations

In the earlier chapters we presented our architecture for cross layer feedback – ECLAIR. Although ECLAIR imposes low overhead, to maximize the benefit from cross layer feedback a well-defined methodology is required for (a) identifying critical cross layer *data items* and (b) minimizing overhead for cross layer feedback. A cross layer *data item* is information that is available at a layer which can be used for cross layer feedback to other layers. For example, bit-error-rate information at the physical layer can be considered to be a data item.

In this chapter we present

- a method for quantifying the *utility* of a data item and using this to identify the critical data items and
- a sub-architecture for cross layer feedback which complements ECLAIR.

Our method of identifying critical data items is explained in Section 6.1. It involves evaluating the *utility* of a data item. This utility is determined by the efficiency improvement of the protocol stack. This efficiency improvement could be in measured by the decrease in *time or space overhead* requirement or decrease in the *data path delay*. These efficiency metrics have been identified in Chapter 5 for evaluation of cross layer architectures. Here these metrics are used for measuring the improvement in protocol stack efficiency. The data items with high utility are considered to be *critical*.

Our sub-architecture, explained in Section 6.2, proposes partitioning the set of critical data items into two sub-sets. One of these subsets is called the *core*. The partitioning is based on the *cost* for cross layer feedback of a data item. This cost could be the power

required for reading a data item from another layer and the power required to make a data item available to other layers. A data item is placed in *core* if the cost of cross layer feedback for the data item is lower when it is placed in the core. Our sub-architecture would aid in further increasing the benefit achieved through cross layer feedback, by decreasing the cost of cross layer feedback of the *core* items.

6.1 Identifying Critical Data Items

To quantify the utility of a data item the exact saving achieved by using the data item needs to be found. This saving could be determined either by precise models, simulations or actual measurements. At the design stage, we believe that the *estimated frequency* of use of the data item, for cross layer feedback, can serve as an indicator of its utility.

Let, d_i be a data item at a layer j. i is an index of the set of data items available for cross layer feedback throughout the stack. For example, some data items are: number of retransmissions (d_1) at the link layer, application priority defined by user (see Receiver Window Control (d_2), Chapter 4) and bit-error rate information at physical layer (d_3). The total number of times, ω_i, the data item is accessed by various layers, other than j, is an indicator of the *utility* of the data item. Critical data items are the ones for which ω_i is high. The designer may choose to define a threshold or cutoff value for ω_i. Now, if $\omega_3 > \omega_1 > \omega_2$ then the items ordered by their criticality are d_3, d_1 and d_2.

After the critical data items have been identified the next step is defining the sub-architecture for cross layer feedback, within ECLAIR.

6.2 Sub-architecture for Cross Layer Feedback

The highlight of our sub-architecture is the creation of a special subset of data items from the critical data items. We call this subset the *core*. A data item is placed in the *core* if the cost of cross layer feedback for the data item is lower when it is placed in the core. Figure 6.1 illustrates the concept of core.

6.2.1 Core

Let the *critical* set of data items available for cross layer feedback be $\mathcal{D} = \{d_i : \omega_i > \upsilon\}$, where υ is a threshold on utility for identifying the critical data items.

Costs related to a data item d_i:
Let,

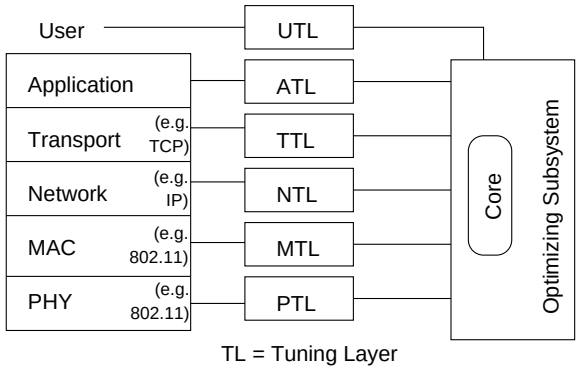

Figure 6.1: ECLAIR with Core

- the cost of writing the data item into the core:

$$\phi'_i = c_w \times \omega'_i \tag{6.1}$$

where,
c_w = cost of a single write of the value of the data item into the core. Assumed to be constant for all data items
ω'_i = estimated frequency of writing the value of the data item into the core

- the cost of reading a data item from the core:

$$\phi_i = c_r \times \omega_i \tag{6.2}$$

where,
c_r = cost of a single read of the data item if it is in core. Assumed constant for all data items
ω_i = sum of estimated frequency of access of the data item by all layers, other than the layer generating the data item value.

- $\bar{c_r}$ = cost of a single read of the data item if it is not in core. Assumed constant for all data items

Def. 6.2.1 (Core Interaction Cost (CIC)) CIC *(Υ_i) of a data item d_i is defined as sum of the cost of writing and reading the data item from the core. From equations (6.1) and (6.2)*

$$\Upsilon_i = \phi'_i + \phi_i \tag{6.3}$$

The total *cost of core* Ψ of core C is the sum CIC of all elements in C

$$\Psi = \sum \Upsilon_i \text{ for all } d_i \in C \tag{6.4}$$

Similarly, the total *utility of core* Θ is the sum of the utilities of all the data items in C

$$\Theta = \sum \omega_i \text{ for all } d_i \in C \tag{6.5}$$

Next, it is to be decided whether an item is suitable for the core or not. For this, the efficiency improvement obtained by putting an item in core needs to be evaluated.

Def. 6.2.2 (Core Potential Score (CPS)) CPS *(κ_i) of a data item d_i is defined as the increase in efficiency by placing the item in core.*

$$\kappa_i = (\bar{c_r} \times \omega_i) - \Upsilon_i \tag{6.6}$$

An item d_i is suitable for the core C only if $\kappa_i > 0$.

Rearranging the terms of equation (6.6) and from equations (6.1), (6.2), (6.3), we get $\kappa_i > 0$, if and only if

$$1 - \frac{c_r}{\bar{c_r}} - \frac{c_w}{\bar{c_r}} \times \frac{\omega_i'}{\omega_i} > 0 \tag{6.7}$$

Since all the terms in equation (6.7) are positive, it can be seen that:

1. If $c_r \geq \bar{c_r}$ then $\kappa_i < 0$ i.e. the data item is not suitable for core

2. If $c_r \ll \bar{c_r}$, $c_w \ll \bar{c_r}$ and $\omega_i' \ll \omega_i$ then $\kappa_i \gg 0$ i.e. the data item is most suitable for core

3. If $c_r \ll \bar{c_r}$, $c_w \ll \bar{c_r}$ and $\omega_i' \approx \omega_i$ then $\kappa_i > 0$

4. If $c_r \ll \bar{c_r}$, $c_w \approx \bar{c_r}$ and $\omega_i' \ll \omega_i$ then $\kappa_i > 0$

   In the above two cases also the data item is suitable for the core

5. If $c_r \ll \bar{c_r}$, $c_w \approx \bar{c_r}$ and $\omega_i' \approx \omega_i$ then $\kappa_i \approx 0$ i.e. the data item is not suitable for core.

6.2.2 Algorithm for Selecting the Elements for Core

Initially C is empty.

Let τ be some *threshold* for the core. The ordering of the data items ensures that first the *high utility* data items are picked for the core. The algorithm is presented in Figure 6.2.

1.
Sort the elements in $\mathcal{D}$ based on their CPS' i.e. the element(s) with the maximum saving is first in the set. Let, $\mathcal{D}'$ be the sorted set of data items.
2.
{Check each element}
for all $d_i \in \mathcal{D}'$ **do**
  {Check net utility if item in core}
  if $\Theta - \Psi < \tau$ **then**
    $C = C \cup \{d_i\}$
  else
    break
  end if
end for

Figure 6.2: Core algorithm

6.3 Example Usage Scenario

In this section we show the use of our sub-architecture, (Section 6.2) through an example. We use an example, since the exact costs for read and write for data items outside core or within core cannot be readily determined. Further, the actual data items can be determined after working with an actual system. In light of this, implementing functionality of core within the ECLAIR prototype is beyond the the scope of this thesis. We assume certain cross layer feedback items (see [65] for a survey on cross layer feedback).

Our example assumes the following $\bar{c_r} = 1, c_r = 0.5, c_w = 0.5$.

Cross layer data items:

For the sake of simplicity, we consider only four data items:

- d_1 = Retransmission information at link layer
- d_2 = Losses acceptable to an application (application layer)
- d_3 = User defined application priority (see Receiver Window Control in chapter 4, Section 4.1)
- d_4 = Wireless channel bit-error rate

Next, we assume some frequency of write and access for the data items.

- d_1: Write frequency $\omega_1' = 50$ per second. The layers that could use this information are (1) TCP, for adapting its retransmission timeout value and (2) application layer to get an estimate of the channel condition and adapt its sending rate. We assume TCP uses this 10 times per sec, while the application uses this information once per second. Thus, $\omega_1 = 10 + 1 = 11$ per second.

- d_2: Write frequency: $\omega'_2 = 1/600$ per second (i.e. application may change its requirements once in ten minutes). The layers that may read this information are link layer and IP layer. Link layer could use this information to adapt its error control mechanisms according to application requirements and channel conditions. IP layer would read this information to determine the interface on which to send the packets. We assume that link layer reads this information 50 times per sec and IP layer reads this information 10 times per second. Thus $\omega_2 = 50 + 10 = 60$ per second.

- d_3: Write frequency: $\omega'_3 = 1/600$ per second (i.e. user may update application priority once in ten minutes). This information may be used by RWC (see chapter 4, Section 4.1) to manipulate the receiver window for current applications. We assume that RWC reads this once every ten minutes. Thus $\omega_3 = 1/600$ per second.

- d_4: Write frequency: $\omega'_4 = 10$ per second (bit-error information from physical layer). MAC, IP, TCP, and application layers may read this information for adaptation. We assume each reads this information 10 times per second. Thus $\omega_4 = 40$ per second.

Based on ω_i the critical data items can be determined. If the cut-off for ω_i was 10, then d_1, d_2 and d_4 would be the critical data items.

Core:

Using this information and the equations (6.1),(6.2),(6.6) we get:

$\kappa_1 = 11 \times 1 - (50 \times 0.5 + 11 \times 0.5) = -19.5$

$\kappa_2 = 60 \times 1 - (\frac{1}{600} \times 0.5 + 60 \times 0.5) \approx 30$

$\kappa_4 = 40 \times 1 - (10 \times 0.5 + 40 \times 0.5) = 15$

From the values of κ_i we can see that d_1 is not suitable for the core since $\kappa_1 < 0$.

Using the *core algorithm* in Figure 6.2, if $\tau = 35$ then d_2 will be in the core.

6.4 Summary

In this chapter we presented a method to identify data items which are useful for cross layer feedback. We also presented our sub-architecture which complements ECLAIR for an efficient implementation of cross layer feedback. This sub-architecture is general and not tied to any specific layer to layer interaction.

The sub-architecture uses information like benefit of using a data item for cross layer feedback, system specific costs for implementing cross layer feedback, and estimated usage frequency of a data item to suggest an efficient implementation strategy. Through a example usage scenario we discussed the use of our sub-architecture.

6.4.1 Limitations of *Core* Optimization Approach

The sub-architecture proposed in this chapter assumes that costs and frequencies for a data item i are known. It is assumed that the following are known: $\bar{c_r}$ – cost of single read of a data item if it is not in core, c_r – cost of single read of the data item if it is in core, c_w – cost of single write to the data item into the core, ω_i' – estimated frequency of writing to the data item in core and ω_i – sum of estimated frequency of access of the data item by all layers. We are not aware of a technique of finding these costs for a device on which cross layer feedback is to be implemented. Further, we have assumed that the costs are identical for each data item. This assumption may not hold in a real system. However, determining the exact costs is beyond the scope of this thesis and does not impact the sub-architecture design.

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To err is human, to forgive design
- Andrew Dillon

Chapter 7

Cross Layer Design and Implementation Guide

In this chapter we present an implementation guide for cross layer optimizations. We first discuss the types of cross layer feedback. We present a guideline for selecting the right architecture based on the type of cross layer feedback. We also provide guidelines for cross layer feedback implementation using ECLAIR.

7.1 Selecting Cross Layer Architecture

To ensure *correct* and *efficient* cross layer feedback, architecture selection should be based on the type of cross layer feedback. Recall from Chapter 2, Section 2.5.1 that the two different types of protocol adaptations are *asynchronous* – adaptation occurs in parallel to protocol execution and *synchronous* – protocol execution proceeds after adaptation. Further, the adaptation required could be *per flow* – separate adaptation for each flow, *across flows* – common adaptation for all flows or *per packet* – protocol adaptation for each packet.

Per flow and across flows cross layer feedback can be done in asynchronous or synchronous manner depending on the optimization requirements. However, per packet is essentially synchronous, since adaptation needs to be done as the packet is being processed.

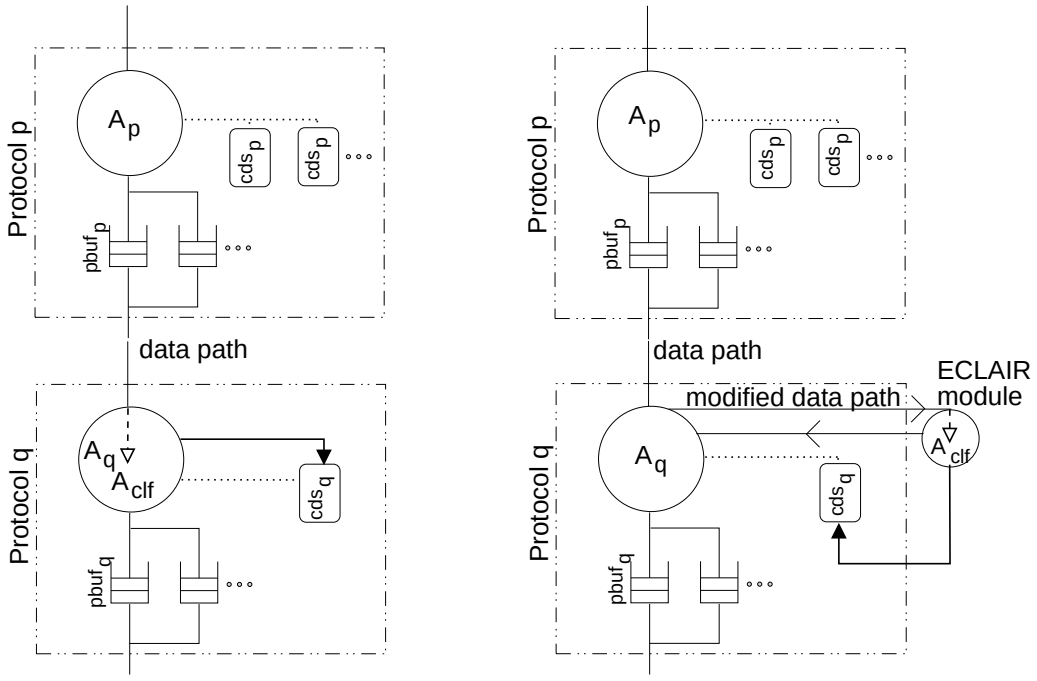
7.1.1 Architecture Selection Criterion: Feedback Type

We believe that the primary criterion for selecting a cross layer feedback architecture is the *sync-type* (asynchronous or synchronous) of adaptation. Incorrect selection would lead to an impact on the correctness and efficiency.

Impact on correctness

The cross layer feedback behavior would be incorrect, if an architecture suitable for asynchronous adaptation is used for synchronous adaptation. For example, cross layer feedback adaptation which is to be triggered by information contained in each packet would fail if an asynchronous architecture like ECLAIR is used.

For per packet (synchronous) cross layer feedback, ISP [81] or CLASS [79] are better candidates (see Chapter 4 for comparison of the various architectures), since both these architectures enable direct interaction between layers and the cross layer algorithm is executed every time the layer code is executed. This is shown in Figure 7.1(a). However,



(a) per packet using synchronous architecture (ISP)

(b) per packet using asynchronous architecture (ECLAIR)

Figure 7.1: Cross layer feedback per packet[1]

in case of ECLAIR, the cross layer algorithm is outside the protocol stack and hence cannot be invoked synchronously for each packet. To use ECLAIR for per packet adaptation, the data path would have to be modified. This is shown in Figure 7.1(b). The figure notation was described earlier in Chapter 5, Section 5.3.1. Recall that, for a protocol, its set of

[1]Refer to Chapter 5, Figure 5.1 for figure notation details

algorithms *(A)* is denoted by a circle, control data structure *(cds)* is denoted by a rectangle with rounded corners, protocol data structure *(pds)* is denoted by an open rectangle with sharp corners, and for the stack the data path is denoted by a solid line between algorithms at adjacent layers. A_{clf} denotes the cross layer optimization algorithms.

Impact on efficiency

As an example, we consider Receiver Window Control (RWC) explained earlier (Section 4.1). In this case, the primary requirement is to apportion application bandwidth such that the bandwidth of each application is in proportion to the user defined priority. It is not essential to tune application bandwidth *synchronously*. For example, reference [54] proposes tuning application bandwidth with each `read()` of an application. Figure 7.2(a) shows the implementation of per and across flows cross layer feedback using a synchronous architecture. Figure 5.2(a) (Chapter 5) shows the implementation specific to RWC (see Chapter 5, Section 5.3.1 for the cross layer notation). Thus, a synchronous architecture such as user-space [54] or ISP [81] would lead to reduction in application throughput (see Chapter 5, Section 5.2 for a comparison of various architectures). However, if an asynchronous architecture, such as ECLAIR is used (Figure 5.2(b)), then the data path delay and hence application throughput is not reduced. Figures 7.2(b)– 7.2(c) show per and across flows cross layer feedback using ECLAIR. As can be seen above, the cross layer feedback implementation would be inefficient if the architecture is not selected as per the sync-type.

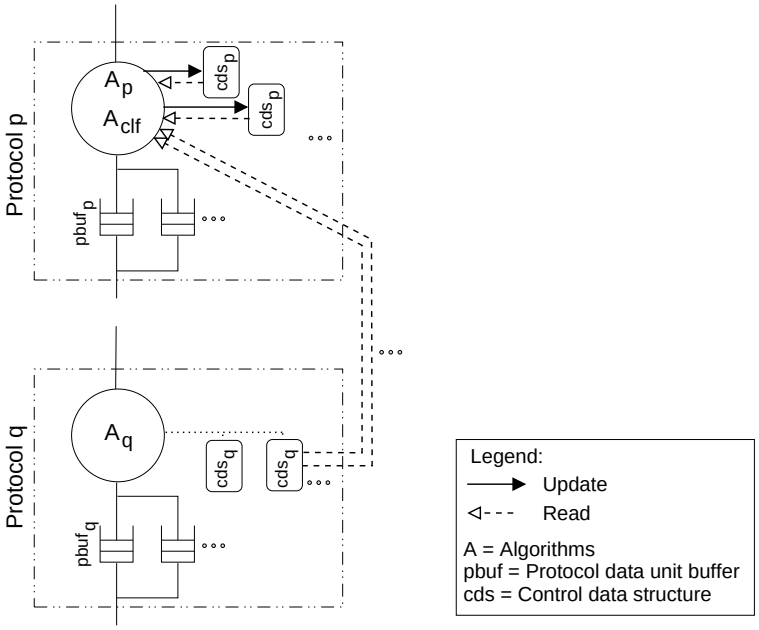
Above, we discussed the impact of architecture selection on correctness and efficiency of cross layer feedback. Next, we discuss architecture selection based on cross layer implementation requirements.

7.1.2 Architecture Selection Criterion: Implementation Requirements

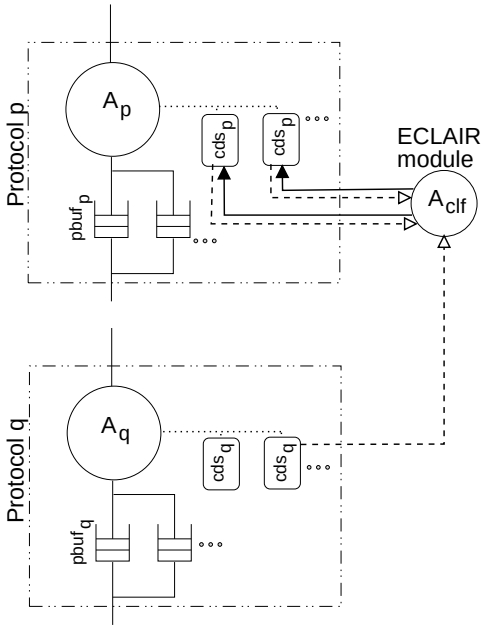
Another important criterion for architecture selection is the implementation requirements. The cross layer architecture evaluation metrics (Chapter 5, Section 5.1), that is, efficiency and maintainability metrics are useful for this.

Metric Weightage: Since there are multiple metrics, weights could be used to help prioritize the metrics. These weights are multiplied with the ranks shown in Table 5.7 (Chapter 5). The sum of the weighted ranks is used to select the appropriate architecture.

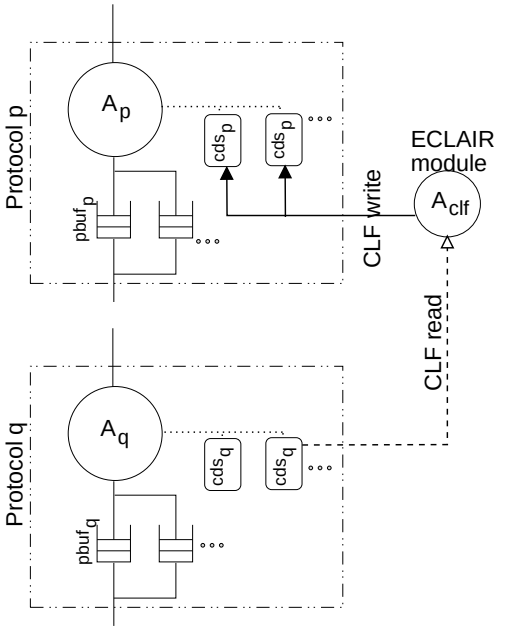
Example: We compare the architectures PMI [34], MobileMan [21] and ECLAIR, in tables 7.1 and 7.2. In the first example, the weights are assigned assuming that efficiency is more important that maintainability. The weighted rank of PMI is 79, for MobileMan it is 72 and that of ECLAIR is 74. For the given weights, MobileMan is a better option. This



(a) per flow / across flows using synchronous architecture



(b) per flow using ECLAIR



(c) across flows using ECLAIR

Figure 7.2: Cross layer feedback per flow/across flows[2]

[2]Refer to Chapter 5, Figure 5.1 for figure notation details

is shown in Table 7.1. However, as shown in Table 7.2, if the weightage of maintainability is also increased (weight of portability and degree of intrusion is increased to 3 each), then the weighted rank of PMI is 82, for MobileMan it is 79, while that of ECLAIR is 77. With the new weights, ECLAIR is a better option.

Table 7.1: Architecture Selection: Weighted Rank - Example 1

Metric category	Metric	**Weightage**	PMI [34]	PMI Weighted	MobileMan [21]	MobileMan Weighted	ECLAIR	ECLAIR Weighted
Efficiency	Time overhead	8	4	32	2	16	3	24
	Space overhead	7	3	21	2	14	4	28
	User-kernel crossing	4	3	12	2	8	2	8
	Data path delay	4	1	4	3	12	1	4
Maintain-ability	Rapid prototyping	2	2	4	4	8	2	4
	Degree of intrusion	2	1	2	4	8	2	4
	Portability	2	2	4	3	6	1	2
	Weighted Rank	–	–	79	–	72	–	74

Table 7.2: Architecture Selection: Weighted Rank - Example 2

Metric category	Metric	**Weightage**	PMI [34]	PMI Weighted	MobileMan [21]	MobileMan Weighted	ECLAIR	ECLAIR Weighted
Efficiency	Time overhead	8	4	32	2	16	3	24
	Space overhead	7	3	21	2	14	4	28
	User-kernel crossing	4	3	12	2	8	2	8
	Data path delay	4	1	4	3	12	1	4
Maintain-ability	Rapid prototyping	2	2	4	4	8	2	4
	Degree of intrusion	3	1	3	4	12	2	6
	Portability	3	2	6	3	9	1	3
	Weighted Rank	–	–	82	–	79	–	77

ECLAIR suitability for Cross Layer Feedback

The above analysis shows that the appropriateness of an architecture is dependent on the priority of the design goals, which can be translated to the metric weights. ECLAIR is suitable when a *balance* of efficiency and maintainability is required.

In the following sections we present an implementation guide for ECLAIR. Since ECLAIR is suitable for asynchronous type of adaptation, we restrict the discussion to asynchronous adaptation.

7.2 ECLAIR Design Guide

In this section we present some design guidelines for cross layer implementation using ECLAIR. Cross layer feedback implementations may have single or multiple optimizations. Accordingly, appropriate trade-offs are required between the design goals.

7.2.1 Single Cross Layer Optimization

In ECLAIR, separating the Protocol Optimizers and Tuning Layers into a separate cross layer system, outside the stack, introduces the overhead of additional function calls. Hence, in case only a single cross layer optimization is planned and the cross layer system is not to be ported / deployed on multiple operating systems then it is better to combine and incorporate the protocol optimizer (PO) and tuning layers (TLs) within the existing stack itself. This would reduce the overhead of multiple calls between PO and TL and hence would increase the efficiency of the implementation. However, this would negatively impact the other cross layer architecture design goals, that is, rapid prototyping, portability and minimum intrusion. Hence, if additional cross layer feedback optimizations are to be introduced later, OSS/PO and TL should be implemented as separate modules. This is to avoid the *maintainability* and *portability* issues later.

7.2.2 Multiple Cross Layer Optimizations

In case of multiple asynchronous type of cross layer optimizations, POs and TLs should be implemented as indicated in the ECLAIR architecture. This would help achieve the design goals (Chapter 2). The use of TLs and OSS/POs helps ensure rapid prototyping, minimum intrusion, portability, efficiency and any to any layer communication.

If multiple cross layer optimizations or POs directly access the layers, then the dependency of the POs is high on the layer's code. Any change to the layer code will lead to a change in all the POs interacting with that layer. Reducing such dependency is useful for ease of maintenance and evolution of the cross layer system. Introduction of a tuning layer, leads to reduction in the coupling between the layer code and POs. Further, *core* should be introduced for reducing the cross layer overheads.

ECLAIR also enables cross layer optimization deployments on mobile devices which have a separate modem. For example, for a laptop which uses a modem for wireless access,

the TLs of MAC and physical layers can be deployed on the modem. These TLs interact with the OSS/POs on the laptop.

7.2.3 Enabling per Flow Adaptation in ECLAIR

In ECLAIR, their is no specific mechanism to enable per flow cross layer feedback. For per flow cross layer feedback, the ECLAIR TL needs to locate the flow that is to be monitored and adapted. For example, in case of TCP at transport layer, the socket identifier (sender port, address and destination port, address) can be used.

7.2.4 Handling Dependency Cycles and Conflicts

A TL does not have any specific components for handling certain issues which are intrinsic to cross layer feedback. For example, *dependency cycles* and *feedback conflict* [41] are not handled by any specific component within ECLAIR. Defining such a component is beyond the scope of ECLAIR. However, ECLAIR components can be used or extended to handle such cross layer feedback problems.

Dependency cycles: Cross layer feedback can lead to adaptation loops involving multiple protocols [41]. Kawadia and Kumar [41] propose creation of dependency graphs for the entire stack. This dependency graph can be used to handle the cross layer feedback cycles. In ECLAIR, a PO registers with multiple TLs. A new PO can be created that registers with all the TLs. This PO can collect information from all TLs and create a dependency graph. If cycles are detected, then appropriate TL's behavior could be changed using this PO. Details about the exact action on detecting dependency cycles is beyond the scope of this thesis.

Cross layer feedback conflict: Cross layer conflict [41] occurs when two or more POs try to update the same data item. A TL can ensure that updates to a data item are spaced out by some time interval.

7.2.5 Filtering Events at TL

A TL monitors the control data structures of a protocol for changes. A change in the value of a data structure is an *event* which is delivered to a PO. However, *raw* information about the value of the data structure may not be useful for a PO. Thus, a *mapping* must be defined for the information about events.This reduces the granularity of event data. For example, the bit error rate information may be mapped to some pre-defined *levels*. A level would contain a range of values. An event occurs when the bit-error rate changes to a different level. This level is sent to the PO within the event notification.

7.2.6 Event Queues for POs

Events which are delivered asynchronously to the PO should be stored in priority queues, by the POs. This would enable a PO to address high priority events first. For example, disconnection event may be of higher priority than other events. This event priority could be defined at a system level.

Before processing an event, a PO may scan the queue to determine protocol adaptation based on the one or more events in the queue. The events which have been *processed* are removed from the queue. This could result in reduced execution overheads in case multiple events occur in a *short* time. However, queue scanning would increase the execution overhead.

In this section we presented some design guidelines for ECLAIR. In the next section we present some implementation guidelines for ECLAIR.

7.3 ECLAIR Implementation Guide

Kernel module background: A kernel module is a binary which can be used to extend kernel functionality. The module can be compiled separately and *loaded* into or *unloaded* from the kernel at run-time without the need for rebooting the system. A loaded kernel module can access the kernel data structures like any other part of the kernel.

7.3.1 Tuning Layer Implementation

A TL can be developed as a separate kernel module or built into the kernel. In either of the cases, TL functions which need to be accessed by POs should be *exported* (see Chapter 3, Section 3.2).

TL as loadable kernel module: This is possible if the required control data structures of the protocol are accessible (see Chapter 3, Section 3.2) without any modification to the existing protocol implementation code. Then the protocol data structures can be read or updated by the TL after loading.

TL built into the kernel: In case the TL is built into the kernel, control data structures of a protocol can be made accessible by following appropriate rules of the C programming language [42]. In this case, the TL should be compiled with appropriate modules in the kernel. For example, TCP TL should be compiled with the *network* modules. This is to ensure that the TL has access to the protocol data structures.

7.3.2 Protocol Optimizer Implementation

Similar to a TL, a PO also can be built into the kernel or developed as a separate module. TLs and POs in user-space are application programs. Each PO and TL can be implemented as a separate module. This provides the flexibility of loading and unloading individual modules as required. However, this increases the function call overheads, if a module calls a function in another module. To reduce the function call overheads, an alternative is to combine related modules into a single module.

7.3.3 Event Notification within the Kernel

For event notification from TL to PO one of the following mechanisms could be used. These mechanisms are for intra-kernel communication.

Synchronous event delivery – Notifier chains:

Notifier chain is a linux kernel mechanism for event communication to interested kernel components. The chain is a linked list of *notifier blocks*. A interested component registers its call back function, through a notifier block, with the component(notifier) that implements the notifier chain. When an event occurs, the notifier traverses the notifier chain and invokes the callback function in each notifier block, thus passing the event notification to interested components.

Asynchronous event delivery – Shared data structures:

A set of data structures can be created which is shared between the TLs and POs. One example is a queue. As compared to notifier chains, the PO may need to *poll* the data structure. Further, *race conditions* and *reader/writer* problems would need to be handled for message queues. Also, a mechanism will be needed for deleting events which have been processed by all the POs. In case of notifier chains, the order of execution of POs is determined by the order within the notifier chain. In case of common data structures, the order is determined by the order in which the POs access the common data structure.

7.3.4 Interaction Across User-Kernel Space

System calls:

System calls are the APIs provided by an operating system to applications in user-space, for example `getsockopt()` and `setsockopt()`. However, the existing system calls enable interaction only with certain components of the operating system. They cannot be used for interaction with new components added, for example a loadable kernel module. Interaction with new components is possible by modifying the implementation of existing system calls or introducing new system calls.

Character device drivers with ioctl:

`ioctl()` is also a system call provided by the operating system. The purpose of ioctl is

to enable manipulation of the parameters of *special* files such as device drivers [23]. This system call can also be used for interaction with kernel modules. In this case, the kernel module needs to be implemented as a character device driver. Applications in user-space can interact with such a module using ioctl.

Event notification to applications:

/proc in Linux:
The `proc` file system is special file system in Linux. It allows creation of virtual files, for example, `/proc/tcp`. Applications can read event information from this `/proc` file. However, the information is available only as a string. Further, special functions need to be defined to be defined by a TL to allow an application to read from the /proc file. Also, the event information has to be *polled* by the application.
netlink sockets:
An overview of netlink and its benefits is provided in references [95, 98]. Netlink socket is a mechanism which enables two-way asynchronous communication between user and kernel-space. In contrast, ioctl and system calls enable one way (user to kernel) synchronous communication between user and kernel space. In ioctl and system calls, kernel to user-space is possible only when the application invokes the call and the kernel returns data in a variable. Through netlink sockets, however, a kernel component can initiate event delivery to an application, without an application invocation first. As compared to system calls, adding a new *protocol type* or a new constant for netlink sockets is relatively simple. Another advantage of netlink sockets is that it supports multicast [98]. This is useful when the kernel needs to send an event notification to multiple applications. Some performance results for netlink sockets and a benchmark tool is available at reference [4].

7.4 Summary

ECLAIR should be used if the cross layer sync-type is asynchronous. Further, POs and TLs should be implemented, as proposed in ECLAIR, if multiple cross layer optimizations are to be implemented or if the cross layer system is to be ported to multiple operating systems. Core should be introduced to reduce the cross layer overheads.

The TL or PO can be implemented as separate modules or as a part of the kernel. Kernel modules have the flexibility of being loaded/unloaded during runtime, without the need for rebooting the system.

Event notification from TL to PO can be done synchronously using callback functions or asynchronously using a queue data structure. Netlink sockets provide a mechanism for two-way asynchronous communication between user and kernel space. Netlink sockets also support event information multicast from kernel to user-space.

Nature's music is never over; her silences are pauses, not conclusions
- Mary Webb

Chapter 8

Summary and Conclusions

In this thesis, we addressed the need for a systematic approach to cross layer feedback. Cross layer feedback is essential for improving the performance of layered protocol stacks deployed over mobile wireless networks. For example, network layer feedback about disconnections can be used to adapt and improve the performance of TCP congestion control algorithm. Cross layer feedback can be implemented on the mobile host or an intermediate host, such as the base station. The focus of this thesis is on cross layer feedback within the mobile host.

We surveyed various proposals for cross layer feedback and highlighted the benefit of cross layer feedback. We also analyzed various cross layer feedback implementation approaches – such as PMI [34], ICMP Messages [73], MobileMan [21], CLASS [79], ISP [81] and user-space implementation [54]. We defined design goals for a cross layer feedback architecture, based on our analysis of existing approaches to cross layer feedback. We defined an architecture ECLAIR which satisfies these design goals. Through analysis and measurements we showed that ECLAIR is a low overhead architecture and aids maintainability. Below we list the contributions of this thesis.

8.1 Thesis Contributions

- We defined the design goals for a cross layer feedback architecture. The design goals are: *efficiency*, *rapid prototyping*, *minimum intrusion*, *portability* and *any-to-any layer communication.*

- We defined a cross layer architecture ECLAIR, which addresses the above design goals. ECLAIR provides a *Tuning Layer* for accessing the control data structures of each protocol. *Protocol Optimizers* contain the cross layer feedback algorithms. They use the APIs of a TL to monitor and adapt a protocol.

  We observed that adaptation of a protocol on receipt of cross layer feedback can be *asynchronous* or *synchronous*. ECLAIR supports asynchronous adaptations since its modules are not embedded within the protocol stack.

- We implemented a prototype of Receiver Window Control (RWC) [54, 66] on a Linux 2.4.19 kernel, to validate ECLAIR. We validated the ECLAIR implementation through experiments over Ethernet and 802.11 wireless LAN. We compared the results with RWC simulations in ns-2 [57].

- We defined metrics to evaluate cross layer architectures against the design goals. We used these metrics to qualitatively and quantitatively compare ECLAIR with existing approaches to cross layer feedback implementation. We also defined a notation to enable easy understanding of cross layer feedback implementations.

  Our analysis shows that ECLAIR is useful when a balance of *efficiency* and *maintainability* is required.

- We measured the overheads of ECLAIR, using the RWC prototype implementation and profiling tools such as MAGNET [28, 103]. Our results show that ECLAIR's impact on data path is negligible as compared to architectures which require modification to the protocol stack. Further, by proper design ECLAIR's user-kernel crossing and data structure search time can be lower than that for user-space implementations which use operating system APIs.

- We proposed a sub-architecture *core* which can be used to select cross layer data items offering high benefit. Core helps to further reduce ECLAIR overheads.

- We also presented a cross layer design guide. We showed that an architecture's suitability is dependent on the cross layer deployment requirements. Incorrect selection can impact the correctness and efficiency. For example, if ECLAIR is used for a case where synchronous adaptation is required, then the cross layer behavior would be incorrect. Further, the stack efficiency will decrease if a synchronous architecture is used where an asynchronous adaptation is required. We presented a simple technique for selecting the appropriate cross layer architecture in line with the implementation requirements. We also presented some design and implementation tips for cross layer feedback implementation on a Linux system.

8.2 ECLAIR Application

Mobile device manufacturers regularly improve their devices for enhancing user experience. Enhancements to the mobile device's protocol stack is also one of the improvements. The protocol stack improvement is aimed at enhanced user experience while on data networks. Besides other optimizations, enabling cross layer feedback within the protocol stack would improve the user experience. For example, as discussed in earlier chapters, battery life could be improved, or download speeds could be improved.

ECLAIR can be used by manufacturers of mobile devices such as mobile phones, PDAs, laptops, etc. to enable cross layer feedback within the device protocol stack. ECLAIR would enable cross layer feedback implementation with minimal modifications to the existing stack. Also, ECLAIR can be used by mobile device manufacturers for rapid prototyping of cross layer feedback protocol optimizations. ECLAIR implementation could be done in hardware or software, as per the requirements of the device manufacturer.

The ECLAIR prototype has been developed on Linux, using certain features of Linux, such as kernel modules. Further, the ECLAIR prototype was developed primarily for the purpose of ECLAIR validation and performance measurement. Hence, the prototype does not check for all the constraints or restrictions imposed by Linux. For other operating systems, some other constraints, restrictions and checks may apply. In addition, the prototype does not fully check or protect against cross layer feedback conflicts or dependency cycles. Thus, ECLAIR may require further detailing before being deployed on commercial systems.

8.3 Future Work

In this section, we present an overview of avenues for further research and how work done in this thesis could be extended.

Improve synchronous cross layer feedback efficiency

We observed that cross layer feedback can be asynchronous or synchronous. We discussed the types of adaptations in Chapter 2. An example of synchronous feedback is adaptation by a protocol for each packet. This type of adaptation decreases the protocol stack execution speed. ECLAIR does not support synchronous adaptation. However, ECLAIR could be used for synchronous adaptation provided it can be synchronized with the protocol stack execution. Another option is modifying the data path of the protocol stack to make it pass through ECLAIR. For example, TCP's `tcp_send` function could be replaced by a new function within ECLAIR PO, which incorporates per packet cross layer adaptation. However, this will require modifications to the protocol stack. In addition, this would lead

to increased data path delay, since per packet adaptation is introduced within the data path. Addition of this component with minimal modifications to the protocol stack, and ensuring that it imposes minimal execution overheads, are an open research questions.

Further, besides ECLAIR, the other architectures which support synchronous adaptation introduce data path delay and hence impact the stack efficiency. It would be interesting to further analyze this and determine optimizations that can be used to reduce the data path delay.

Enhancement of ECLAIR sub-architecture

Any implementation of cross layer feedback will impose some overheads on the system. To minimize these overheads, we have proposed a preliminary method for selection of *high utility* cross layer data items. These data items are placed together in a sub-system called *core*, to minimize the cross layer feedback overheads of these data items. For this thesis, we assumed that the collective frequency of access of a data item, by the various layers, is a measure of its utility. Further, we assumed that the read (or write) costs for all data items are similar. For implementation on actual devices, it is essential to develop proper models for determining the utility of a cross layer data item. Further, the exact read and write costs need to be determined for the device on which cross layer feedback is to be implemented. This will help in identifying appropriate cross layer feedback data items, and minimizing the cross layer feedback costs.

ECLAIR for base station and other network nodes

We proposed ECLAIR – an architecture for mobile device protocol stacks. The design goals defined were also for a cross layer architecture on a mobile device. However, ECLAIR could be extended for use on base station, routers and other network nodes. This would require addition or changes to the design goals and accordingly extensions to ECLAIR.

As discussed earlier in Chapter 1, cross layer adaptations at a base station would need to be suited to each device connected to the base station. Thus, some of the important requirements would be: support for a large number of connections, facility to identify connections from the same device and support for efficient interaction with the mobile device – to enable information exchange with it. For addressing these requirements, ECLAIR would need to be suitably extended. For example, for supporting large number of connections, the architecture would require a facility for creation of additional Tuning Layers and Protocol Optimizers as the connections grow. Also, an additional *device component* would be needed for information exchange with each devices. Lastly, Protocol Optimizers would need to interface with this device component to determine adaptations specific for each device.

ECLAIR for Seamless mobility

Seamless mobility requires feedback between protocols at the same layer. For example, when moving from a wireless local area network to a wireless wide area network, feedback would be required between 802.11 MAC and GPRS MAC. ECLAIR provides Tuning Layers (TL) for each protocol. In Chapter 3, Section 3.4, we presented an example of seamless mobility using ECLAIR. However, some extensions would be required to enable ECLAIR to provide information to the network entities, to support seamless mobility. ECLAIR provides a *user* TL which can be used for interaction with external entities. An additional *network node component* may be needed that interacts with the network nodes. This component would send device status and other information to the network nodes and receive information from them. The seamless mobility PO can now use this network information for adapting the device protocol stack. Details of the network node component, issues related to efficient information exchange with the network entities and issues related to simultaneous tuning of multiple protocols on the device, are open research questions.

Extending ECLAIR to resolve cross layer conflict and dependency cycles

ECLAIR is an architecture for implementing cross layer feedback. There are certain issues, such as cross layer feedback conflict and dependency cycles [41], which are intrinsic to cross layer feedback.

Cross layer feedback involves modifying the behavior of the existing protocols, for example, modifying TCP's retransmit timer to change its retransmit behavior. However, there could be a *conflict* as multiple POs, besides TCP itself, may want to change the value of TCP's retransmit timer. It is important to determine which one of the writes to a protocol's *control* data structure is *correct* at a point in time. Further, cross layer feedback can lead to adaptation loops involving multiple protocols [41]. A mechanism is required to trap and resolve such *cross layer feedback conflicts* and *cycles*.

ECLAIR does not provide a direct solution to these cross layer issues. However, ECLAIR provides the components which can be used to solve these issues. An overview was provided in Chapter 7 as to how ECLAIR components can be used to handle these issues. We had stated that a PO can be created that collects information from all TLs and detects cycles. This PO can be used to modify behavior of certain TLs. The existing TLs do not have any provision for behavior modification through a PO. The TLs can be extended to support this. Further, for conflicts we stated that a TL can detect conflicts and introduce time delays for updates to a protocol through POs. This too needs additional research. For example, a protocol itself may also update its data structures. The TL should be able to detect this also. Also, in this context it needs to be determined

whether TLs should immediately update protocol data structures or delay the update and combine the update of multiple POs.

The list, above, of open research issues is not exhaustive. There could be other issues related to cross layer feedback architecture, which have not been discussed above and need further research.

Appendix I

Additional Tuning Layer APIs are listed below. Please see Chapter 3 for rest of the APIs. Socket identifier is the 4-tuple – source address and port, destination address and port.

I-1 TCP TL APIs

•*Name:*	get_rtt()
Input Parameters:	socket identifier
Returns:	Round Trip Time of a flow (Number) | Return Code (Number)
Description:	Locates the socket and returns the round trip time

•*Name:*	get_retx_timer()
Input Parameters:	socket identifier
Returns:	Value of flow's retransmit timer (Number) | Return Code (Number)
Description:	Locates socket and returns the retransmission timer value

•*Name:*	set_rtt()
Input Parameters:	Socket identifier, value of rtt (Number)
Returns:	Return Code (Number)
Description:	Locates socket and updates the round trip time

•*Name:*	set_retx_timer()
Input Parameters:	Socket identifier, retransmit timer value (Number)
Returns:	Return Code (Number)
Description:	Locates socket and updates retransmit timer value

•*Name:*	cancel_retx_timer()
Input Parameters:	[Socket identifier]
Returns:	Return Code (Number)

Description: Locates socket(s) and cancels the retransmit timer. If no socket identifier is specified then the timers of all the TCP flows are canceled.

•*Name:* enable_retx_timer()
Input Parameters: [Socket identifier], timer value (Number)
Returns: Return Code (Number)
Description: Locates socket(s) and restarts the retransmit timer, with the specified value. If no socket identifier is specified then the timers of all the TCP flows are restarted with the specified value.

I-2 Mobile-IP TL APIs

•*Name:* get_solicitation_timer()
Input Parameters: –
Returns: Timer (Number) | Return Code (Number)
Description: Returns the solicitation timer

•*Name:* get_current_solicitations()
Input Parameters: –
Returns: Solicitations (Number) | Return Code (Number)
Description: Returns the number of solicitations sent

•*Name:* get_max_solicitation_interval()
Input Parameters: –
Returns: Max interval (Number) | Return Code (Number)
Description: Returns the maximum solicitation interval

•*Name:* set_solicitation_timer()
Input Parameters: Timer (Number)
Returns: Return Code (Number)
Description: Updates the solicitation timer

•*Name:* set_current_solicitations()
Input Parameters: Solicitations (Number)
Returns: Return Code (Number)
Description: Updates the number of solicitations sent

•*Name:* set_max_solicitation_interval()

Input Parameters: Max interval (Number)
Returns: Return Code (Number)
Description: Updates the maximum solicitation interval

I-3 802.11 MAC TL APIs

- *Name:* get_fragmentation_threshold()
  Input Parameters: –
  Returns: Current fragmentation threshold (Number) | Return Code (Number)
  Description: Returns current packet fragmentation threshold

- *Name:* set_fragmentation_threshold()
  Input Parameters: Fragmentation threshold (Number)
  Returns: Return Code (Number)
  Description: Sets packet fragmentation threshold

- *Name:* get_round_trip_time()
  Input Parameters: –
  Returns: Round trip time (Number) | Return Code (Number)
  Description: Returns round trip time to next hop

- *Name:* get_signal_strength()
  Input Parameters: –
  Returns: Received Signal Strength (Number) | Return Code (Number)
  Description: Returns current received signal strength

- *Name:* get_recv_queue_status()
  Input Parameters: –
  Returns: Receive queue status (Number) | Return Code (Number)
  Description: Returns the % of queue filled, of the current interface

- *Name:* get_send_queue_status()
  Input Parameters: –
  Returns: Send queue status | Error (Number)
  Description: Returns the % of queue filled, of the current interface

- *Name:* get_current_bandwidth()
  Input Parameters: –
  Returns: Bandwidth (Number) | Error (Number)
  Description: Returns the bandwidth of current interface

- *Name:* get_packet_errors()
  Input Parameters: –
  Returns: Received packet errors (Number) | Return Code (Number)
  Description: Returns number of packets received with error

I-4 802.11 Phy TL APIs

- *Name:* get_bit_errors()
  Input Parameters: –
  Returns: Current bit error rate i.e. bits per 10^5 (Number) | Return Code (Number)
  Description: Returns the current bit error rate

- *Name:* get_channel()
  Input Parameters: –
  Returns: Current channel (Number) | Return Code (Number)
  Description: Returns currently selected channel for transmission

- *Name:* set_channel()
  Input Parameters: Transmit channel (Number)
  Returns: Return Code (Number)
  Description: Sets the transmission channel

- *Name:* get_sensitivity_threshold()
  Input Parameters: –
  Returns: Sensitivity Threshold (Number) | Return Code (Number)
  Description: Returns the sensitivity threshold

- *Name:* set_sensitivity_threshold()
  Input Parameters: Sensitivity Threshold (Number)
  Returns: Return Code (Number)
  Description: Updates the sensitivity threshold

•*Name:*	get_noise_level()
Input Parameters:	–
Returns:	Noise level (Number) | Return Code (Number)
Description:	Returns the current noise level

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List of Publications

Journal/Magazine

1. V. T. Raisinghani and S. Iyer. Cross-layer Design Optimizations in Wireless Protocol Stacks. *Computer Communications (Elsevier)*, 27(8):720–724, May 2004.
   (Survey of cross-layer feedback research; Chapter 2)
2. V. T. Raisinghani and S. Iyer. Cross-layer Feedback Architecture for Mobile Device Protocol Stacks. *IEEE Communications*, 24(1):85-92, Jan 2006
   (ECLAIR overview, related work and short comparison of ECLAIR with existing work. In addition, presents RWC implementation and evaluation; Chapters 2, 3, 4)
3. (submitted) V. T. Raisinghani and S. Iyer. Cross-layer Architecture for Mobile Wireless Devices. *IEEE Transactions on Mobile Computing*
   (Presents detailed qualitative and quantitative evaluation of ECLAIR and architecture selection guide; Chapters 5,7)

Conference

1. V. T. Raisinghani and S. Iyer. Architecting Protocol Stack Optimizations on Mobile Devices. *IEEE/ACM COMSWARE*, New Delhi, India, Jan 2006.
   (ECLAIR details, related work, summary of comparison with existing architectures, RWC implementation and evaluation and ECLAIR optimization; Chapterss 2,3,4)
2. V. T. Raisinghani and S. Iyer. Analysis of Receiver Window Control in Presence of a Fair Router. In *IEEE ICPWC*, New Delhi, India, Jan 2005.
   (Shows that Receiver Window Control is goodput preserving and does not adversely impact competing traffic. Not included in this thesis).
3. V. T. Raisinghani and S. Iyer. ECLAIR: An Efficient Cross Layer Architecture for Wireless Protocol Stacks. 5^{th} *World Wireless Congress*, SF, USA, May 2004.
   (ECLAIR details; Chapter 3).
4. V. T. Raisinghani and S. Iyer. User Managed Wireless Protocol Stacks. In 23^{rd} *ICDCS*, 2003. Poster. (Proposes cross-layer feedback from user; Chapter 2)
5. V. T. Raisinghani, A. K. Singh, and S. Iyer. Improving TCP Performance over Mobile Wireless Environments using Cross Layer Feedback. In *IEEE ICPWC*, New Delhi, India, December 2002.
   (Discusses benefits of Cross Layer Feedback. Presents Receiver Window Control and ATCP; Chapter 2).

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