Cross-Layer Contextual Interactions in Wireless Networks

Ruwini Edirisinghe and Arkady Zaslavsky

***Abstract*—Future wireless networks should facilitate efficient communication for rapidly growing bandwidth intensive applications. The existing layered protocol stack lacks efficiency in handling such applications. Cross-layer interactions can operate within the existing protocol stack and are a promising solution. In this article we present a survey of cross-layer interactions in wireless networks. We classify the cross-layer solutions based on the nature of the adaptation using a systematic evaluation of existing approaches. We identify critical criteria applicable to generic cross-layer framework design. Further, we analyze the existing generic cross-layer frameworks and qualitatively compare them based on the identified criteria. Context awareness is an essential and important element of future pervasive and wireless technologies. We propose to consider the context awareness as an essential and important aspect in cross-layer interactions and adaptations. We discuss context parameters with respect to adaptations that can be enabled at the layered protocol stack. Finally, we discuss open research challenges and gaps to be filled in cross-layer interactions in wireless networks.**

***Index Terms*—Cross-layer interactions, cross-layer framework, context awareness, context exchange, context definition, adaptations.**

I. Introduction

THE LAYERED protocol stack has been used as an elegant mechanism in inter-networking static wired networks. Communication systems use layered protocol stack for a number of reasons. Firstly, according to ISO-OSI reference model [93], the initial purpose of layering was to ensure modularity. In a modular system each module has clearly defined functions, procedures and specified and controlled interactions among modular components to enable layer independence. Because of the abstracted modular components, the overall system is easy to understand. Hence, layered approach reduces system design complexity. Secondly, layering ensures easy implementation and maintainability. Thirdly, the layered approach assures the inter-operability between different systems. Standardized abstractions allow designers of various subsystems to focus on their particular subsystem without bothering about the entire system inter-operability.

Though strict layered approach serves as an elegant solution for inter-networking static wired networks, it is argued that the layered protocol stack is not adequate for efficient functionality of wireless networks [81], [84]. There are few reasons for this argument. Firstly, the nature of wireless networks is different to that of static wired networks for which the layered stack was proposed. Wireless networks are highly dynamic in nature and have limited network resources. Inherent dynamic nature and complexity of network together with limited resources and computational capabilities of wireless devices necessitate adaptations [32] and performance improvements of entities in the protocol stack [50]. The layered protocol stack is insufficient to cater for these adaptations of demanding applications and complex networking conditions. Secondly, wireless system performance improvements through joint multi-layer interactions are stifled in layered approach. Thirdly, as noted in [81], strict standards can easily restrict innovation. Moreover, it is argued that, the standards should be kept minimally prescriptive so that standard can leave present and future researchers to innovate [81].

This article presents a holistic review of cross-layer interaction and identifies knowledge gaps. The article is organized as follows. Section II discusses the solutions that attempt to address the limitations of layered protocol stack for wireless LANs[1]. We argue that the cross-layer interaction is a viable solution among the solutions proposed. We present our classification of cross-layer solutions as specific and generic solutions in Section IV-C. Further, design guidelines and critical criteria for generic cross-layer framework design are presented. Existing generic frameworks are qualitatively compared based on the design criteria in this section. Section IV presents the importance of context awareness in cross-layer interaction. Parameters identified during analysis in Section IV-C are also presented in this Section. Section V discusses the open research challenges and gaps to be filled in the area. Finally, Section VI concludes the article.

II. Cross-Layer Interactions

Different proposals in the literature attempt to address the problems of layered protocol stack for wireless networks. The solutions include non-stack based architectures and cross-layer interactions.

Non-stack based network architecture [8] proposes an alternative to traditional layered network protocol architecture by introducing new non-layer abstractions. For example, Role Based Architecture (RBA) based on totally new abstractions called roles, was proposed in [8]. Instead of using protocol layers, RBA organizes communication using functional units that are called roles. However, it is arguable to which extent

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[1]We use terms "WLAN", "wireless networks", "wireless systems" interchangeably unless differences are explicitly specified and terms primarily mean wireless local area networks (WLANs)

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the RBA could replace the existing layered network model which has been deployed all over as a powerful network architecture.

Cross-layer interaction [32] is another solution proposed to overcome limitations/inefficiencies of layered protocol stack for wireless networks. Since non-stack based architectures with totally new abstractions such as RBA are considered as *layer replacements* and they do not conform to concept of layering at all, these solutions require replace and redesign of existing protocol stack entirely. Alternative proposal of cross-layer design is considered as an extension or modification to existing layered protocol architecture. In the point of view of deployment, adaptation and acceptance by the community, solutions that can coexist with the layered stack such as cross-layer interactions are significantly important. Hence, cross-layer design is considered as a promising solution over non-stack based architectures.

Cross-layer design is defined as "Protocol design by the violation of a reference layered communication architecture with respect to that particular layered architecture" [79]. According to aforementioned definition, designing protocols by violating the reference architecture, through direct communication between protocols at nonadjacent layers or sharing variables between non adjacent layers is *cross-layer design* with respect to the reference architecture. This definition is further extended [79] with the fact that violation of layered architecture includes creating new interfaces between layers, redefining the layer boundaries, designing protocols at a layer based on the details of how another layer is designed, joint tuning of parameters across layers and giving up the flexibility of designing protocols at different layers independently.

Even though the cross-layer interaction can lead to viable wireless network architecture, the benefits are achieved at a cost. The potential issues of cross-layer interactions are identified as follows:

- Implementation of cross-layer interaction is complex because it necessitates modifications to the protocols at different layers. Carefully designed cross-layer framework should ensure minimal changes to the existing layered protocol stack. As argued in [4], once cross-layer design is adapted, maintenance is difficult because any upgrade or change in protocols must be coordinated among different protocol layers. Hence, the design should ensure easy maintenance and upgrade.
- The cross-layer design should preserve the modularity of the layered architecture, so that it ensures uninterrupted operation to the layered stack and interoperability. However, Interoperability between cross-layer and non-cross-layer systems will be complex.
- It is argued in [39], that the cross layer interactions can affect not only the particular layer, which executes cross-layer adaptation but also the other parts of the system. Implementation may introduce unintended consequences (due to unintended dependencies of system components) on overall system performance. Further, it is discussed that cross-layer interactions can cause adaptation loops that are parts of different protocols which interact with each other [39]. So, dependencies and conflicts among interactions should be carefully managed.

Hence, to achieve the advantages of cross-layer interactions, framework should be carefully designed and implemented. Exploitation of cross-layer interactions through concurrently implemented adaptations should have capability to handle dependencies to avoid unintended consequences.

Cross-layer designs are surveyed and classified based on the functionality [28]. A cross-layer coordination model is proposed with the assumption that cross-layer interactions are intended to solve four specific problems including security, mobility, quality of service (QoS), and adaptation of the wireless link, thus leading to four coordination planes in the model. This survey covers only four specific cross-layer interactions and the underlying assumption is too strict to provide a holistic and a generic survey of cross-layer interactions.

Survey presented in [79] includes detail definition of cross-layer interactions and types of the various approaches that can violate layered abstractions in the stack in order to support the definition. However, detailed analysis of these layer interactions with the objectives of the type of adaptation or optimisation that they intent to enable are not discussed. Even though some of the open research challenges primarily focusing at design considerations are discussed in [79] a holistic view of various stages from design, implementation to system standardisation through evaluations are not considered. One open research challenge at implementation stage as a cautionary perspective of having concurrent multiple adaptations is presented in [39] and elaborated through an example. Cross-layer interactions are surveyed in [36] with the emphasis on VANETs. This study particularly looked at interactions available as a combination of each layer for example, Cross-layer design for transport-MAC layers, Cross-layer design for transport-network layers and Cross-layer design for transport-network-MAC layers.

A coherent high-level view of cross-layer awareness and generalization of the cross-layer awareness in wireless networks are still gaps to be filled. Also, the exploration of context parameters of the protocol stack which could lead to various multiple concurrent adaptive situations is neglected in previous studies. These are the motivation of this research paper.

III. Classification of Cross-Layer Solutions

We classify the existing cross-layer interactions systematically with a holistic view of the overall system. Cross-layer interactions are mainly categorized as *generic* and *specific (non-generic)* solutions. Figure 1 shows the classification of existing cross-layer solutions selected based on the interest and within the scope of this article.

We define the *specific solutions* as the cross-layer interactions tailor towards specific requirement of an application or protocol. We define *generic solutions* as the architectures which are applicable to wide range of cross-layer interactions and are not designed specifically for a particular applications.

Specific cross-layer solutions are further classified based on the nature of interaction they support. Solutions which focuses on single layer adaptations based on the parameters acquired from the other layers are categorized as *single-layer solutions*. Solutions which focuses on joint adaptations

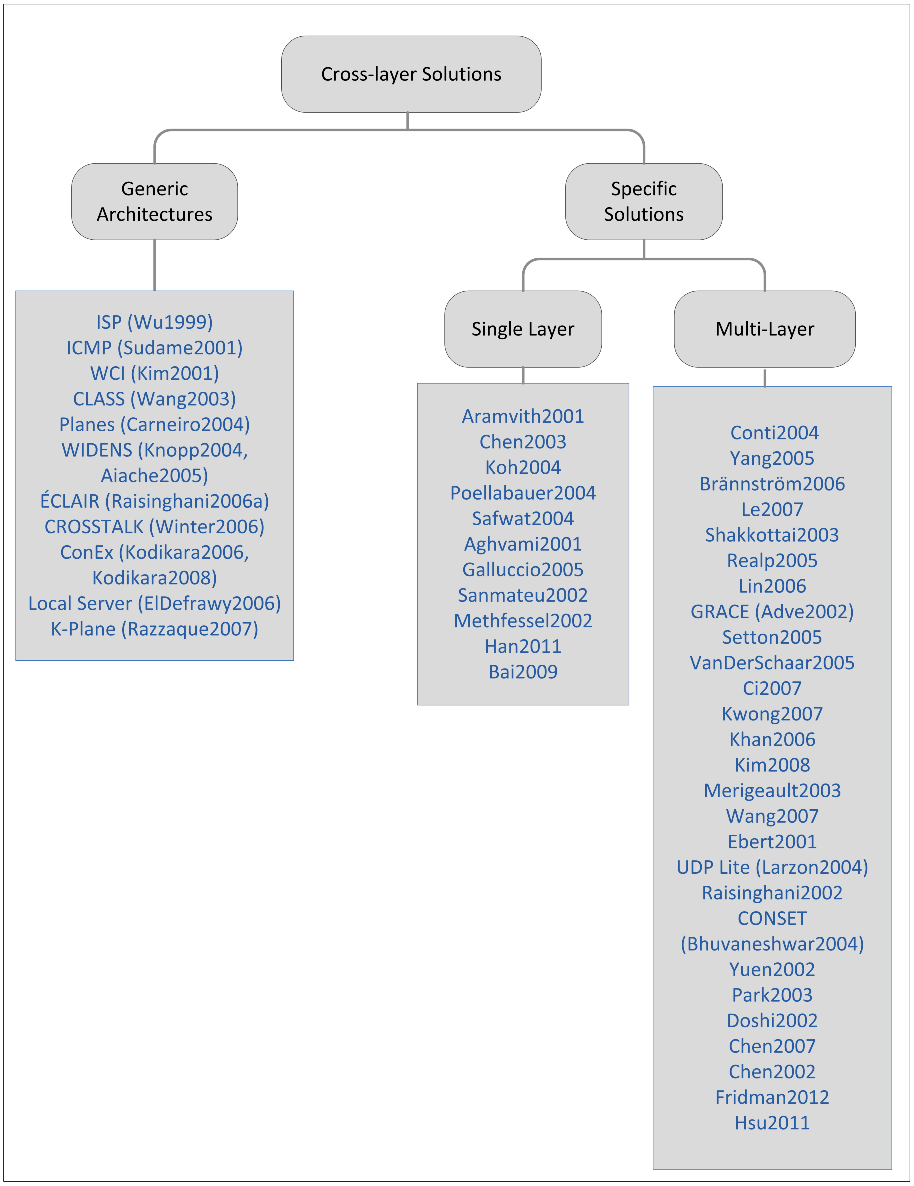

Fig. 1. Classification of Cross-layer Solutions

of multiple layer protocols or applications are categorized as *multi-layer solutions*. Detailed definitions, examples and algorithms related to these cross-layer solutions are discussed in following sections.

Terms related to the discussion within the scope of this article are formally defined as follows. Five layer protocol architecture which is composed of application layer, transport layer, network layer, data link or Medium Access Control (MAC) layer and physical layer is considered, throughout the discussion from this point onwards.

Entity

Entity E_{xi} is defined as the i^{th} protocol or application at x^{th} layer, L_x of the protocol stack. Let $E_x = (e_{x1}, e_{x2}, ..., e_{xp})$ be collection of all protocols and applications at layer x of the protocol stack, where $x \in \mathbb{Z}^{+=5}$, $1 < i < p$ and $p \in \mathbb{Z}^+$. p is the total number of entities at L_x. The collection of entities of the whole system E, is such that $E = (E_1, E_2, E_3, E_4, E_5)$. $\mathbb{Z}^+$ denotes positive integers and $\mathbb{Z}^{+=5}$ denotes the positive integers less than or equal to 5.

Active Entity

An active entity is defined as an entity involved in context aware adaptation where the entity automatically adapts to context by changing the entity‘s behaviour. Let $AE_x = (ae_{x1}, ae_{x2}, ..., ae_{xq})$ be the set of all active protocols and applications at layer x which are interested in cross-layer context to execute the adaptation. AE_{xj} is j^{th} active protocol or application at x^{th} layer, L_x of the protocol stack where, $x \in \mathbb{Z}^{+=5}$, $q \in \mathbb{Z}^+$ and $1 < j < q$. q denotes the total number of active entities at layer,

L_x. $AE_x \subseteq E_x$ so that $q <= p$. The collection of active entities of the whole system AE, is such that $AE = (AE_1, AE_2, AE_3, AE_4, AE_5)$ where, $AE \subseteq E$.

Context Parameter

Context parameter is any type of data useful for context aware adaptation that can be discovered or measured in the system. Let k^{th} Context parameter be denoted by c_k where, the total number of context parameters that can be discovered in the system is r where, $r \in \mathbb{Z}^+$ and $1 < k < r$. k^{th} context parameter at time t is denoted by c_k^t
For example, context parameter Signal to Noise Ratio (SNR) at time t can be denoted by c_1^t.

Specific cross-layer solutions will be briefly discussed in next section and are used to identify the adaptations that can be enabled and corresponding parameters at each layer. Generic solutions will be discussed and analyzed in detail in the Section III-C.

A. Specific Cross-layer Solutions

As stated above, specific Cross-layer solutions are classified as single-layer and multi-layer context aware adaptations from cross-layer interaction point of view. In single-layer context aware adaptations an *active entity* at a particular layer of the protocol stack executes the adaptive algorithm using one or more *context parameters*. Context can originate at any layer of the protocol stack. In joint multi-layer adaptations multiple *active entities* from multiple layers jointly execute a common adaptive algorithm using one or more *context parameters*

A number of researches have been done in the literature on specific cross-layer solutions. These solutions are designed to achieve a specific adaptation, performance enhancement or entity requirement and generally are not extensible for other adaptations due to the specifically specified structural characteristics.

Single-layer Specific Cross-layer Solutions

Objective of the specific cross-layer solution is to execute a specific adaptation or performance enhancement of an entity (active entity) at a particular layer. This execution is based on the information obtained from entities at the other layers including non-adjacent layers. Processing and monitoring of various layer parameters are done either by the active entity or through an external plane. For example, Quality of Service (QoS) parameters can be monitored by the application itself or by a separate QoS management entity on behalf of the application according to the interest of the application. Such solutions are called single-layer cross-layer solutions because the performance improvement is the objective of only a particular layer, and the other layers just provide the necessary context parameters. Figure 2 depicts a single-layer adaptation with respect to the layered protocol stack. As shown in the figure, active entity at layer $n+1$ executes a specific adaptation based on context parameters acquired from the entities at layers n and $n-1$.

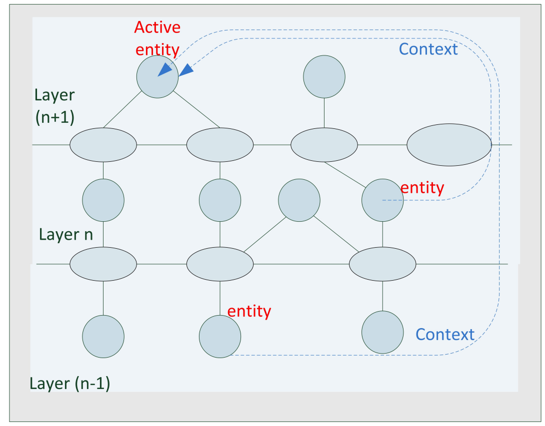

Fig. 2. Single-layer adaptations.

Execution of an adaptation algorithm of single-layer adaptations is shown in Algorithm 1. As shown in the algorithm, an active entity ae_x at a particular layer x is involved in context aware adaptation. c_j is the context parameter required for the adaptation. Entities providing context are represented as e_{yj} where y is the layer at which j^{th} context parameters are originated. Execution of adaptation begins at ae_x. Once the context need arises ae_x acquires the context through context exchange mechanism (e.g. by polling e_{yj} through direct interaction or through an interface). Then ae_x executes the adaptation based on the acquired context parameters.

Algorithm 1 Single-Layer adaptation Algorithm

while true **do**
Require: ae_x be an active entity at single-layer x executing context aware adaptation.
e_{yj} be j^{th} entity at layer y providing context parameter c_j.
Ensure: in 5-layer stack $x, y \in \mathbb{Z}^{+=5}$, $n, j \in \mathbb{Z}^+$, where $\mathbb{Z}^+$ is set of positive integers
begin
context parameter need at ae_x
context parameter c_j exchange from e_{yj} to ae_x
ae_x executes adaptation
end
end while

Selected single-layer adaptations are discussed as follows.

Application Layer Adaptations: A mechanism for channel adaptive media source rate adjustments is suggested in [5]. This solution proposes a rate-control scheme, which encodes the video sequences with better motion continuity which takes the effects of the encoder buffer fill-up and the channel feedback information into consideration. Similarly, Adaptive Encoder is proposed in [30], where MPEG encoder is controlled in order to adapt its emission rate to the current bandwidth offered by the wireless link. Transcoding techniques are used to minimize the energy cost in mobile systems [67]. According to this approach, dynamic transcoding introduces additional processing to reduce transmission power, hence making the device more energy efficient, in contrast to the traditional ways used to reduce the energy requirements such as code off-loading or frequency or voltage scaling.

Transport Layer Adaptations: Mobile SCTP (mSCTP) [51] is proposed for soft handovers in transport layer. mSCTP is based on Stream Control Transmission Protocol (SCTP) [80]. mSCTP uses network layer information and depends on the rules for triggering to add and to change the IP addresses for on-going associations during the handover. Speculative techniques are used for network throughput improvements over a lossy links based on transport layer algorithms [6]. This is based on speculation algorithm at transport layer. A transport layer protocol based on channel conditions is proposed in [16]. The video transport protocol used in [16] was Universal Datagram Protocol (UDP) in conjunction with a congestion control mechanism extended with an end-to-end loss differentiation algorithm. The algorithm differentiates various packet loss patterns such as losses due to network congestion and losses due to channel breakdown/outages. This solution uses partial checksum and multiplexing to Internet Protocol(IP) and hence reduces packet loss rate.

Network Layer Adaptations: A Dynamic Multi-Attribute Cross Layer Design (DMA-CLD) approach for wireless ad hoc and sensor networks is proposed in [72]. DMA-CLD is executed at network layer based on application, MAC and physical layer parameters and information gathered from intermediate nodes. A proposal to use link layer handover notifications to reduce the handover latency of MobileIP [66] at network layer is presented in [73]. Mobile device reconfiguration to satisfy application and user quality requirements by switching between different radio access technologies is proposed in [2]. The mechanism of reconfiguring the radio system is based on the ability to meet user needs in terms of application performance and quality of service needs.

Link Layer Adaptations: Adaptive link layer strategies are executed with the objective of energy efficient data transmission in [33]. The proposed mechanism uses strategies including power efficient link adaptation, exploitation of multi-user diversity and trading bandwidth for energy efficiency to reduce base station energy consumption. It is shown that increase of IEEE 802.11 MAC level retransmissions to avoid TCP retransmissions, can decrease the power consumption [59]. Power control mechanism proposed in [59] avoids throughput reduction due to TCP retransmissions that occur when the channel conditions are poor leading to delays at link layer.

Multi-layer Specific Cross-layer Solutions

A joint multi-layer adaptation with respect to a layered protocol stack is illustrated in Figure 3. As shown in the figure, active entities at layer $n+1$ and n jointly execute an adaptation. The active entity at layer $n+1$ acquires the context parameters needed for the adaptation from an entity at layer n and two entities at layer $n-1$. Also, the active entity at layer n acquires the context parameters from entities at layers $n-1$ and n.

Execution of the adaptation algorithm of a joint multi-layer adaptation is shown in Algorithm 2. As shown in the algorithm active entities involved in joint adaptation are ae_{xi} and context parameters required for adaptation c_j are as defined above. Entities providing context are represented as e_{yj} , where y is the layer at which context parameter is

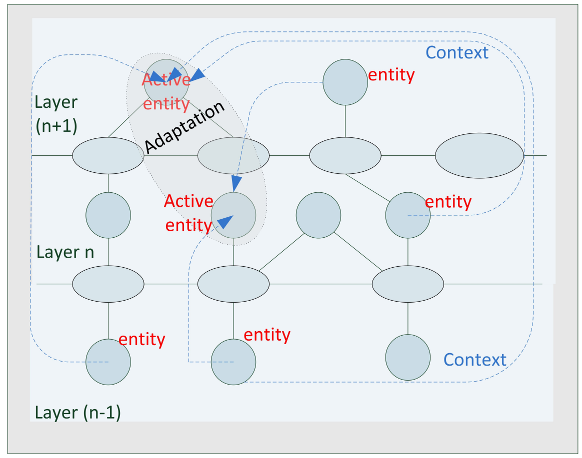

Fig. 3. Joint multi-layer adaptations.

originated. For each active entity involved in joint adaptation, execution of adaptation is initiated at ae_{xi}. Context parameters are exchanged when the need for context arises (e.g. by polling e_{yj} through direct interaction or through an interface). Then each of ae_x executes the adaptation based on the acquired context parameters.

Algorithm 2 Joint multi-layer adaptation Algorithms

while true **do**
Require: ae_{xi} be i^{th} active entity at layer x jointly executing context aware adaptation across multiple layers.
e_{yj} be j^{th} entity at layer y providing context parameter c_j.
Ensure: in 5-layer stack $x, y \in \mathbb{Z}^{+=5}$ $n, j, i \in \mathbb{Z}^+$, where $\mathbb{Z}^+$ is set of positive integers
begin
for active entity i **do**
context parameters need at ae_{xi}
context parameters c_j exchange from e_{yj} to ae_{xi}
ae_{xi} executes adaptation
end for
end
end while

A number of studies have been carried out on cross-layer solutions related to joint adaptations involving more than one entity from multiple layers. These solutions are called multi-layer solutions because entities from more than one layer involve in achieving a common joint optimization or adaptation objective. The adaptations that can be enabled at each layer of the protocol stack are illustrated in Figure 4. Joint cross-layer adaptations addressed by various studies are identified as a combination of two or more single layer adaptations.

Selected joint multi-layer adaptations proposed in the literature are categorized and discussed below. These joint multi-layer adaptations proposed in each study can be analyzed as a combination of single layer adaptations. The summary of the analyses is presented in Table I.

Joint Multi-layer Mobility Management: Mobility Support Architecture (MSA) integrates the benefits of application layer

TABLE I
JOINT MULTI-LAYER ADAPTATIONS.

Research	Application Layer	Transport Layer	Network Layer	Data Link Layer	Physical Layer
Yang et al. [89], Shabdanov et al. [75]			adaptive routing	rate/channel adaptation	
Conti et al. [19]		congestion control & rate control	adaptive routing	channel scheduling	
Lin et al. [56]		congestion control	adaptive routing	channel scheduling	power control
Realp et al. [71]				channel scheduling & rate/channel adaptation	
Shakkottai et al. [76]		congestion control		channel scheduling	
Setton et al. [74]	coding & packetization	congestion control	adaptive routing	channel scheduling	modulation
VanDerSchaar et al. [83]	QoS control				adaptive modulation & power control
Ci et al. [18]	QoS control & coding	rate control	adaptive routing	channel scheduling & link rate adaptation	adaptive modulation
Khan et al. [40]	QoS control			channel scheduling	
Merigeault et al. [58]			adaptive routing		adaptive modulation
Kim et al. [43]	packetization		adaptive routing		
Wang et al. [85]	packetization			link rate adaptation	power control
Lin et al. [55]	packetization			link rate adaptation	
Larzon et al. [53]	packetization	congestion control		error detection	
Doshi at el. [23]			adaptive routing	link rate adaptation	power control
Yuen at el. [91], Costagliola et al. [20]			adaptive routing	link rate adaptation	
Bhuvaneshwar et al. [7]			adaptive routing		power control
Park et al. [62]			adaptive routing	link rate adaptation	
Chen et al. [13]			adaptive routing	link rate adaptation	
Brannstrom et al. [9] Le et al. [54]	application layer mobility management		network layer mobility management		
Raisinghani et al. [69]	QoS control	congestion control	mobility management		
Hsu and Hefeeda [35]	adaptive encoding and QoS control	prioritisation			adaptive modulation
Fridman et al. [29]	power control and modulation	adaptive scheduling and link rate adaptation			

mobility using Session Initiation Protocol (SIP) with network layer mobility using Mobile Internet Protocol (MIP) [9] for heterogeneous networks including IEEE 802.11 WLANs. A cross-layer information system provides context for mobility adaptation. MSA is a cross-layer mobility management solution which functions in the mobile device. Similar concept is suggested in [54] introducing cross-layer module at Home Agent (HA) of MIP and Servicing-Call Session Control Function (S-CSCF) of IP Multimedia Subsystem (IMS). The cross-layer module resides at the mobile device's home network in this solution. Since, the binding update is translated and used to trigger the registration procedure in IMS signaling between mobile device and home network is reduced.

Joint Multi-layer Resource Allocation: Providing efficient methods for allocating network resources on applications over the Internet is addressed in [76]. Sharing MAC and physical layer knowledge of the wireless medium such as instantaneous radio channel conditions, traffic, congestion conditions with higher layer needs such as capacity requirements are discussed. Further, it is argued that multi-user diversity gains can improve network throughput. The need of multi-cell studies for WLANs is highlighted. Multi-User Diversity (MUD) with cross-layer approach was studied in [71] in IEEE802.11e environment. Performance enhancement through the MUD scheduling combined with link adaptation of heterogeneous wireless systems is discussed. The multi-hop resource allocation in wireless systems is studied in [56]. Detail study of optimization-based cross-layer resource allocations mapped to different layers of the protocol stack is presented in this study. Congestion control at the transport layer, routing at the network layer, and scheduling or power control at the MAC or physical layers are presented in [56]. The Global

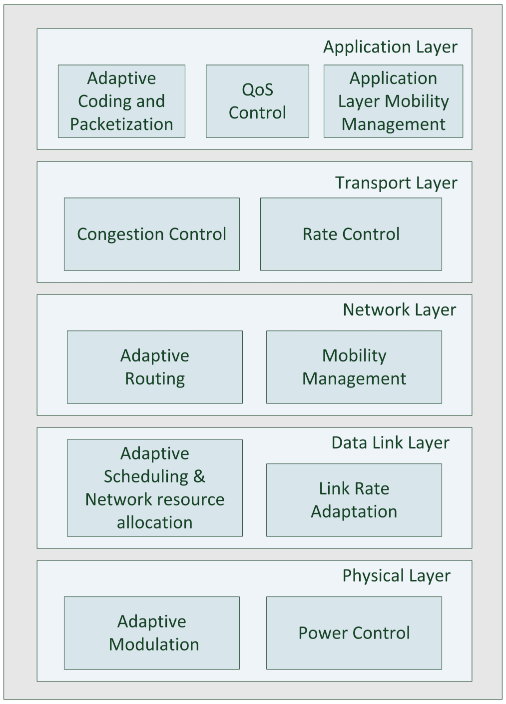

Fig. 4. Adaptations Identified at Each Layer

Resource Adaptation through CoopEration (GRACE) project [1] addresses the cross-layer resource adaptation. Resource manager in GRACE allows multimedia applications to make an energy-aware processor resource reservation, and makes admission control based on both processor utilization and energy availability.

A comprehensive survey of resource reservation approaches for IEEE 802.11-based wireless networks including the joint multi-layer adaptations are presented in [90].

Joint Multi-layer Video Streaming: Real-time video streaming and quality of service support in wireless networks are discussed in a number of studies. The study of states-of-the-art in cross-layer design for QoS support in multi-hop wireless networks is presented in [92] in detail. The need for cross-layer design techniques in the realization of end-to-end (E2E) QoS is highlighted in some studies [10]. New architecture is proposed for the wireless multimedia by jointly optimizing the protocol stack at each station and the resource exchange among stations [83]. In this proposal, application, MAC and physical layer interaction for selecting the optimal modulation scheme and optimal power consumption are discussed. Further, multimedia quality fairness is considered in [83]. The cross-layer design proposed in [74] is specifically for real-time video streaming. The framework considers the joint adaptation of adaptive modulation at link layer, capacity assignment at MAC layer, congestion-optimized routing at network layer, congestion-distortion optimized scheduling at transport layer and secure coding and packetization at application layer. Link layer techniques are used to adjust parameters according to channel conditions and to improve link throughput and the achievable capacity region of the network. It is argued in [74] that joint allocation of capacity and flow at the MAC and network layers optimize the supportable traffic rate. As a result, end-to-end video quality is enhanced. An integrated cross-layer framework for multimedia streaming over wireless networks [87] and wireless multi-hop networks [18] with routing at network layer are proposed. Key characteristics of [18] this approach are the quality-aware multimedia streaming and the globally optimal control policy which involves interaction among application layer network layer and physical layer. Layer parameters are mapped to source encoding, source decoding, network and service models to jointly interact with quality aware cost function and delay-quality optimization.

A novel cross-layer optimization approach across multiple layers that jointly optimize the user satisfaction is proposed in [40]. In this approach, application layer, data link layer, and physical layer of the protocol stack jointly optimize an application oriented objective function. A Mechanism to support context exchange with the objective of supporting quality of service through the protocol stack is proposed in [58]. Two interfaces called Channel Adaptation Layer (CAL) and Source Adaptation layer (SAL) at mobile device are introduced. Further, CAL at wireless access point and SAL at remote host are introduced. The adaptation layers are such that the cross-layer context information generated from one layer as packets are later interpreted and reorganized by the other layer upon receipt of the packet. Control of application layer message generation jointly with network layer is proposed [43]. In particular, dynamic adjustment of the video transmission rate based on the channel bandwidth as well as minimized the error propagation during handoff provides seamless and high quality video streaming over the mobile WiMAX network.

Application layer adaptation based on parameters from lower layers is necessary for effective multimedia communication [55]. Cross-layer optimization scheme is proposed for High Definition scalable video streaming over wireless environment by jointly considering video content rate-distortion characteristics, channel conditions, transmission duration, and QoS constraints [55]. A framework for optimizing the quality of video streaming is proposed in [35]. Joint optimisation objectives are achieved by interactive parameters at various layers: at wireless channel, the link layer and the distortion of the video streams in the application layer.

Designing cross-layer communication protocols for multimedia, is systematically reviewed further in [57]. In this study, [57] reviewed above discussed literature under the two categories of Unequal Error Protection (UEP) and Joint Compression and Communication Optimization.

Joint Multi-layer Transport Protocols: UDP Lite [53] proposes a lightweight version of UDP for real time multimedia applications with increased flexibility in the form of partial checksum. UDP Lite introduces the packets to be divided in to two parts. One part is with more sensitivity to errors and the other part with less sensitivity to errors. The solution enables the application to specify whether the errors are acceptable in order to reduce the number of unnecessary discarded packets. UDP Lite suggests not having a partial check sum at the link layer to allow damaged packets to be delivered. Then it is recommended to modify device driver to ignore checksum errors of incoming frames carrying UDP packets. So the packets are delivered to transport layer. Whether they should be discarded or not is decided by UDP Lite. TCP performance improvement over wireless environment using cross-layer feedback is suggested in [69]. Two approaches are discussed. One is Receiver Window Control (RWC) and the other one is ATCP. In RWC approach, RWC dynamically incorporates user specified application priorities and adjust the advertised window and thus throughput. For example, for high priority applications receiver window is increased. In ATCP approach, ATCP uses network layer feedback in terms of disconnections and connection signals, to modify the congestion control mechanisms of TCP, thereby achieving enhanced throughput in mobile wireless environments [69].

Joint Multi-layer Routing: Performance improvement of routing protocols using MAC and physical layer information is proposed in [91]. In this solution, efficient transmission rate is achieved utilizing the channel estimations exchanged from physical layer. Further, it is proposed that routing algorithms can exhibit various properties based on the MAC layer information provided. Bandwidth awareness, interference awareness and congestion awareness are introduced. Energy and delay efficient cross-layer routing is proposed based on Optimized Link State Routing (OLSR) protocol [20]. Minimum energy routing is proposed with efficient caching techniques to store the minimum energy route information [23]. Joint interaction of network, MAC and physical layer, allows minimum transmit power calculation based on received signal strength and energy aware route maintenance. Moreover, a proposal for power aware routing protocol called CONSET (CONnectivity SET) based on channel-gain and directional information obtained from link layer Request to Send (RTS), Clear to Send (CTS) control packets compatible the IEEE 802.11 standard is presented in [7]. Ultimately, RREQ packets are broadcast at minimum power required to maintain network connectivity. A route discovery and route optimization mechanism based on channel information is suggested in [62]. The proposed routing metric called Route Outage Probability (ROP) minimizes packet loss due to fading. ROP is applied to Multi-Route Path Selection (MRPS) scheme that selects links based on channel conditions. Joint adaptation of physical, MAC and network layer facilitates the channel aware route selection. A general cross-layer framework for multihop adhoc wireless network optimization is proposed in [13]. The traffic of network is specified using a sequence of routing matrices. A mechanism to determine throughput of each node, each route and the entire network for a given network topology using physical layer conditions and aforementioned sequence of routing matrices is introduced. Routing protocol is used in assisting data accessibility in [15]. The primary objective of the mechanism is to provide a data accessibility service for a group of mobile users so that they can access desired data with high success rate. The QoS routing protocol is used to assist data advertising, lookup and replication services to achieve high data access success rate.

Joint Multi-layer Network Performance Improvement: To overcome network performance problems, the MobileMan project allows cooperation of layers through cross-layer interaction of IEEE 802.11 technology [19]. Cross layer architecture in MobileMan adds another stack component called Network Status which is accessible by each layer. MobileMan supports local and global adaptations to network functions. Non-cross-layer optimized protocols can still function within the framework. However, there is a limited extensibility of the solution for non-network-status-oriented entities. Even for network-status-oriented entities there is a need of redesigning the existing stack. Network performance enhancement based on cross-layer processing between physical, IEEE 802.11 MAC and network layers is proposed in [89]. MAC layer transmission rate adjustment based on channel signal strength information is suggested. Furthermore, the overall network performance improvement is achieved using congestion information from MAC layer in route discovery at network layer. A research study [75] formulates a cross-layer optimization framework for the routing and scheduling problem jointly with physical layer techniques including successive interference cancellation, superposition coding, dirtypaper coding and their combinations. OMAN [29] is a muti-layer network design proposed to maximise communication performance objectives. The network resource allocation was jointly done through various network design options including adaptive power control, adaptive modulation, flow control and scheduling.

Joint Multi-layer Energy Efficiency: It is shown that energy saving is achievable through a combined tuning of the data link layer and physical layer [25]. Further, this study [25] argue that harmonized operation of power control and medium access control can lead to reduction of energy consumption of WLANs. Cross-layer approach for energy efficiency of image delivery over wireless sensor networks is proposed in [85]. Desirable Bit Error Rate (BER), retry limit, frame length and transmission data rate are jointly optimized with the objective of minimizing total energy consumption of image bit stream transmission. Hence, different network resources are allocated on different components of encryption.

B. Design Attributes of Generic Cross-layer Architectures

Having presented the specific cross-layer solutions in Section III-A, this section defines the fundamental design attributes which will assist in analysis and qualitative comparison of the generic cross-layer architectures which will be discussed in section III-C.

Context Exchange Overhead: Context exchange is the mechanism used to convey the context parameters across the layers to the active entity. Context exchange overhead is determined by the average size of context data unit and signaling frequency. Different signaling mechanisms use different data units such as messages, packets, triggers and function calls.

Two categories of context exchange can be identified. One is the mechanisms that support local adaptations within the mobile device. In this circumstance, the internal context exchange overhead is considered. Second category of mechanisms supports global adaptations which involve the interaction with the external access network. For global adaptations external context exchange overhead is considered.

Context exchange overhead is a cost to a given architecture because transmission and processing time of data units are proportional to data overhead. Hence, excess signaling should be minimized for efficient operation. Cost benefit analysis and selecting optimal data unit sizes and frequencies are vital.

Context Exchange Latency: Context exchange latency refers to the propagation time of signaling mechanism. It is the time that signaling mechanism takes to transmit context data units from context source to destination (active entity). Latency is determined by the travel time between context source, destination pair and the processing time in the propagation path(if any).

Context exchange latency is a cost to a given architecture because it may slow down the execution performance and hence system performance. Hence, excess signaling latency should be minimized for performance objectives. Smaller context exchange overhead can reduce context exchange latency.

Scalability: Scalability of the system refers to the ability to add multiple adaptations to the architecture without significantly affecting the performance of the existing protocols or applications. This indicates the flexibility and extensibility of the architecture to wide range of adaptations or performance enhancements. Scalable architecture is flexible enough to handle adaptations which requisite interaction among any combination of layers in the protocol stack. Scalability is a plus to a given architecture. Generic architectures should be able to extend the cross-layer signaling to various other adaptations beyond the interaction it currently supports.

Design Complexity: Design complexity is the degree to which the cross-layer interaction requires interface design and modifications to various components of the system such as the existing protocol stack and operating system. Architectures with less design complexity are easy to implement and easy to prototype. Such architectures enable easy development of new cross-layer adaptations either independent of or with lesser number of modifications to the existing layered protocol stack. Moreover, the design complexity should not hinder the flexibility to port the implementation in to different platforms and systems.

Design complexity of overall network architecture is also important especially in global adaptations. The design of the architecture should not recommend modifications to network components such as radio access points, access routers and the gateways as the context messages traverse through the network. Moreover, context should flow transparently in the network so that nodes which are not interested in cross layer information do not need any modification.

Coexistence with Layered Stack: This refers to the ability of the cross-layer architecture to operate in the existing layered protocol stack without hindering the operations of non-cross-layer entities or degrading the performance of the stack. Modifications to the stack to enable cross-layer interactions impact the execution performance and such modifications should be kept at a minimal level. Cross-layer architecture should ensure uninterrupted operation of non-cross-layer functionalities of the existing protocol stack. Design of cross-layer architecture should provide cross-layer functionalities only to cross-layer interested internal entities (with in mobile device) and external nodes (in the access network). Further, the design of cross-layer architecture should have the facility to dynamically enable or disable easily.

Modularity: This refers to the degree to which the cross-layer architecture preserves modularity without violating the layered reference architecture. Modularity indicates how the design of cross-layer architecture enables interactions in an organized manner. It is manifest that cross-layer interaction inherently requires some interaction among non-adjacent layers. However, it is vital to maintain the coupling of the protocol stack to a minimum degree to preserve the standardization. Attempts to preserve modularity in cross-layer design may increase the number of interfaces and hence context exchange latency. But, balanced solutions of cost-benefit are extremely important for next generation wireless networks.

Maintainability: Maintainability refers to the ability of protocols or applications to easily upgrade or change in future. In layered protocol architecture, entities at one layer can evolve independently without disrupting the functionalities of entities at another layer.

As argued in [4], when cross-layer design is adopted, any upgrade or change in protocols must be coordinated among different protocol layers. Further, it is noted that coordinated upgrade requirement significantly limits the capability of product evolution through innovation. However, well-designed cross-layer interaction should not hinder product evolution and allow maximum degree of maintainability through the aforementioned design attributes such as less design complexity and ability to coexist with existing stack.

C. Generic Cross-layer Architectures

We argue that a complete cross-layer architectures is composed of context exchange, context representation and context manipulation mechanisms [48]. Signaling between layers is an integral and essential part of a context exchange mechanism. Some of the architectures discussed in this section consider mainly signaling between layers. Since cross-layer signaling forms the core of context exchange [50] these mechanisms are included in the paper. Cross-layer signaling mechanisms particularly for cognitive networks are reviewed in [44]. Internal and inter-node signaling mechanisms appropriate for selected cognitive network proposals are analyzed with a qualitative evaluation of each mechanism. Following are the generic cross-layer architectures proposed to date including the cross layer exchange mechanisms.

Wireless Protocol Stack with Interlayer Signaling Pipe-ISP

Wireless protocol stack with Interlayer Signaling Pipe (ISP) is proposed in [88]. System architecture of the protocol stack adopted from [88] is shown in Figure 5.

ISP carries cross-layer information vertically across layers layer-by-layer fashion. It is suggested that the cross-layer information to be specified in a Wireless Extension Header (WEH), which is part of IPv6 header and can be read by wireless access supporting routers and the end users. The ISP at Mobile Host (MH) spans across from application layer to wireless physical layer. At radio access point ISP proposes physical and data link layer replacement with ISP Radio Link Protocol (RLP), wireless MAC (WMAC) and wireless Physical (WPHY) layers. The ISP at remote Host (RH) covers only the layers from application to IP. Only the routers supporting wireless access and the corresponding RH and MH communicating with each other can read the content of WEH while other routers ignore it during the transmission.

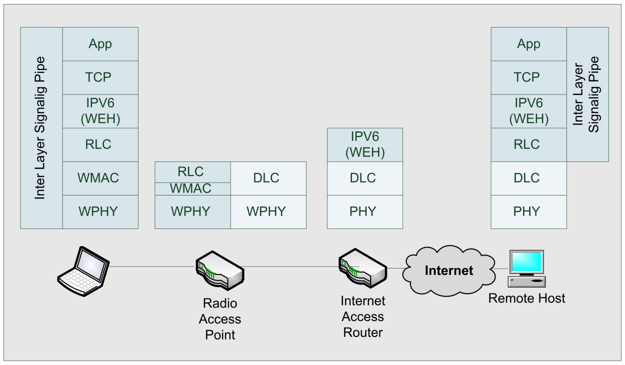

Fig. 5. Interlayer Signaling Pipe wireless Protocol stack

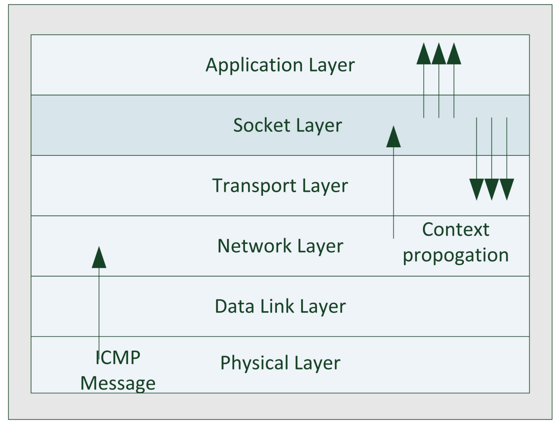

Fig. 6. ICMP messages to propagate cross-layer information

The Internet Access Points (IAP) reads the WEH and gets the information for routing, radio link control, medium access control and physical layer transmission control.

The protocol stack presented in [88] is exclusively designed for wireless networks. Further, ISP can support adaptations of the mobile node at lower layers which needs context information from higher layers. However, this approach has some bottlenecks. Signaling overhead of ISP based protocol stack is high because cross layer information is wrapped in IP packets. Propagation latency of the internal signaling is high because the information has to traverse layer-by-layer fashion to the destination layer. Further, lack of focus for the local adaptations limits scalability of the solution. It is less flexible due to two reasons. Firstly, the cross-layer feedback information traversal from lower-layers to higher layers locally within the same mobile host is not supported. Secondly, any arbitrary layer cannot request cross-layer context from the system. Further, modularity of the proposal is low because, the whole layered stack is coupled through a signaling pipe. The ISP wireless protocol stack proposes a total stack replacement at mobile nodes and Radio Access Point and significant replacement to the layers above IP at Remote Host. So, coexistence with the existing layered architecture is low. Complexity is high due to the protocol changes required. As a result this ISP proposal is difficult to maintain too.

ICMP Messages based cross-layer signaling-ICMP

A mechanism based on ICMP messages for propagating information about the network environment to higher layers of the protocol stack is proposed in [82]. The network environment is defined as a set of parameters such as latency, bandwidth, energy, cost, signal strength and location. Changes to the parameters (events) are informed to the interested protocol layers. The objective is to reduce the overhead of polling for the changes by individual protocols. Noticeable changes are specified using upper and lower margins (watermarks). When an event occurs, ICMP message is generated and propagated to transport layer and application layer successively (through a function invocation by the handler at the socket layer). Message propagation of the proposal adopted from [82] is shown in Figure 6.

The mechanism based on ICMP messages, provides comprehensive event reporting and network information propagation to the higher layers. Further, it is designed to minimize the overhead and processing of individual cross-layer context aware protocols by notifying the protocols rather than allowing them to poll the lower layers. Since, ICMP messages are used in cross-layer signaling and only interested parties can involve in cross-layer interaction, this scheme does not interrupt the operation of non-cross-layer entities. So, this proposal can coexist with the layered protocol stack. But, whether cross-layer interactions can be dynamically enabled and disabled is not mentioned. Due to the standard ICMP messages used, the scheme does not require complex changes in network infrastructure or software. However, event reporting mechanism demands lower layer protocol changes. So, the design complexity and maintainability is at a moderate level. The mechanism does not require direct communication between protocols hence preserves the modularity to a certain extend. However, direct interaction among lower layers by added socket interface violates the concept of layer abstraction for some performance objectives. So, the modularity is at a moderate level. Even though, the solution tries to avoid the polling overhead on individual protocols, since the cross-layer context is wrapped in ICMP messages the context exchange mechanism has high overhead. Layer by layer propagation of context introduces high latency. Another limitation of ICMP signaling mechanism is that it cannot support the adaptations at lower layers which require upper layer information. Further, layers other than application and transport cannot express the interest for cross-layer context. The solution is less flexible to support adaptations that require context other than the network environment context. So, the scalability is low.

Wireless Channel Information Service-WCI

A network service for wireless channel information is proposed in [42]. The solution defines the channel condition parameters such as general link characteristics, bandwidth, latency, packet error rate and connection loss to be exchanged between WCI services and adaptive applications. The WCI server holds wireless channel conditions as XML objects.

Cross-layer context exchange in WCI service is based on HTTP protocol. The proposal has a higher degree of coexistence with the existing layered architecture and since

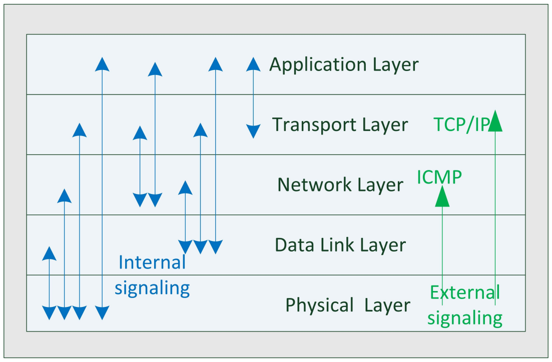

Fig. 7. CLASS Framework

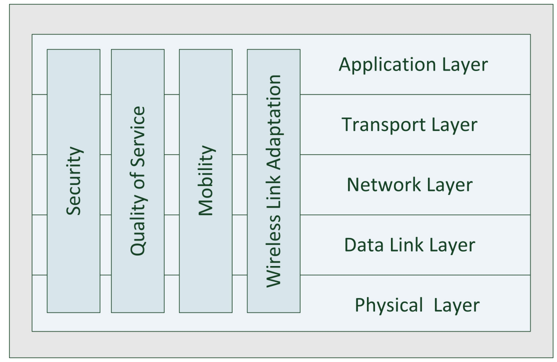

Fig. 8. Coordination Planes based Cross-layer Framework

context flows through layer-by-layer across the existing protocol stack, modularity is preserved. Context access mechanism at mobile device is simple. However, considerable complexity is introduced to context acquisition, and reporting at the server. So, the design complexity is at a moderate level. The solution is easy to maintain. All wireless channel information conveyed to upper layers is coming through the access network hence, the overhead and latency of signaling mechanism is high. Supporting local adaptations are not considered as an objective of this solution. Not every layer can get context through the signaling mechanism. Specially, lower layers cannot adapt to upper layer parameters. So, the scalability of the solution is low.

Cross-Layer Signaling Shortcuts-CLASS

The cross-layer signaling framework is suggested in [84] is called Cross-Layer Signaling Shortcuts (CLASS). CLASS proposes direct signaling between non-neighboring layers. Internal message format of CLASS is defined with the objective of supporting local adaptations. External information flow is based on standard ICMP and TCP/IP headers. Class signaling mechanism is shown in Figure 7, which is adopted from [84].

The direct signaling across the layers proposed by CLASS inherently has a very low latency. The mechanism is highly flexible, because any protocol or application at any layer can exchange context. So, wide range of adaptations can be supported. Internal signals are light weighted but the external messages are wrapped in either ICMP or TCP/IP headers so introduces some overhead. Hence, average signaling overhead is moderate. However, direct interaction among the protocols introduces high design complexity and maintenance difficulty. Moreover, CLASS proposal violates the concept of layered protocol stack by direct signaling among layers for performance objectives, so the solution does not preserve the modularity.

Cross-layer Coordination Planes

A framework based on cross-layer coordination planes for wireless terminals is proposed in [12]. Cross-layer coordination model composed of four coordination planes where each of them is viewed as a cross-section of layered-protocol stack. Four coordination planes are proposed as security, QoS, mobility, and wireless link. Internal details of signaling or interaction mechanisms are not available. Network architecture of the Wireless Channel Information Service adopted from [12] is illustrated in Figure 8.

Coordination planes separate the wireless networking problems from the existing functionality of the layered stack hence solution enables uninterrupted operation to the existing stack. So this concept has high degree of coexistence in the layered stack. Due to the cross-section views introduced as coordination planes, modularity of the proposal is low. Implementation and changes to the existing protocols and providing operations of planes is complex. Similarly, the maintenance is also difficult due to the complexity in changing and evolving the protocols. Flexibility is low since the adaptations are limited to the ones defined in coordination planes. Moreover, the system cannot support adaptations which may involve interaction among the planes. So, scalability of cross-layer coordination model is low.

WIreless DEployable Network System-WIDENS

The WIreless DEployable Network System (WIDENS) [3], [46], is an ad-hoc communication system specifically designed for public safety or emergency applications. WIDENS architecture supports combination of several joint optimizations such as secured QoS extension for route optimization, mobility management, resource allocation at the MAC layer with hard QoS support, combine opportunistic scheduling and channel coding and slotted multiuser/stream capability. According to [46], the cross-layer interactions in the framework are supported through parameter mapping between adjacent layers as illustrated in Figure 9.

WIDENS cross-layer architecture preserves modularity to a great extent, by allowing layer-by-layer interactions. Cross-layer interaction is separated from non-cross layer information flow and ensures uninterrupted operation of non-cross-layer entities, so the solution can coexist with the existing layered protocol stack. However, providing mapping function with the separated standard protocol functionality is complex and demands synchronization mechanisms. Further, support for wide range of adaptations needs complex and massive number of changes to the protocols. So, design complexity is high maintenance is difficult. The processing overhead of context passed to the next layer is very high due to mapping of state information and parameters of adjacent layers. In addition

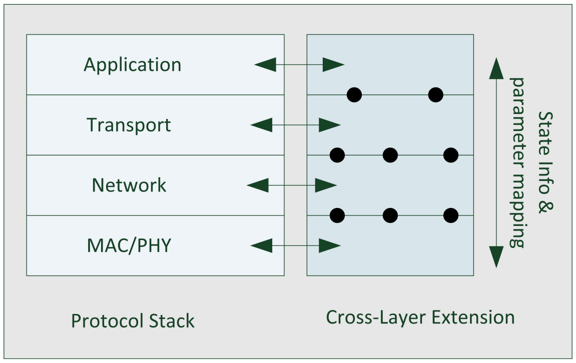

Fig. 9. WIDENS Cross-layer architecture

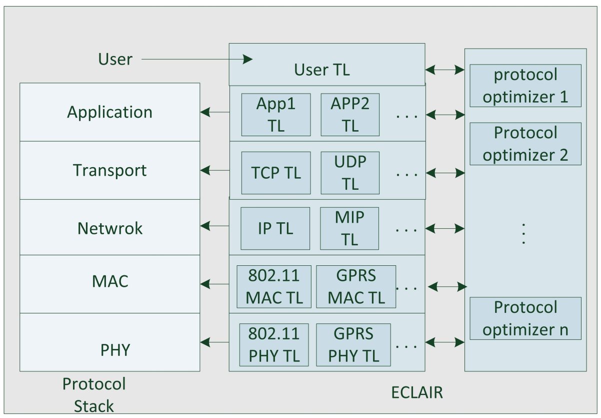

Fig. 10. ECLAIR Cross-layer architecture

to that, latency of layer-by-layer traversal and processing at each layer is very high. However, unnecessary and unintended cross-layer operations can be avoided by controlling information flow through the translation at each layer. Each newly added adaptation requires changes to whole protocol stack that the packets flow through. So, flexibility of the architecture to support range of adaptations is low.

ECLAIR Cross-layer Architecture

ECLAIR architecture proposed in [68], is based on the fact that protocol behavior is determined by the protocol data-structures. ECLAIR provides an interface to read and update the protocol data-structures through the interface called a Tuning Layer (TL) at each layer. TL is further divided in to generic tuning layer and implementation specific tuning layer for portability objectives of implementation. Cross layer feedback algorithms and data structures are added in to Protocol Optimizers (PO). The collection of POs forms the Optimizing SubSystem (OSS). ECLAIR architecture adopted from [68] is shown in Figure 10.

ECLAIR cross-layer architecture is separated and can be easily enabled or disabled and it facilitates the uninterrupted operation to the layered protocol stack. Modularity of the system is high because it allows layer separation and preserves the modular functionality. Cross-layer interaction can be facilitated at any layer, and solution can be extended to range of adaptations and optimizations through OSS, so the scalability

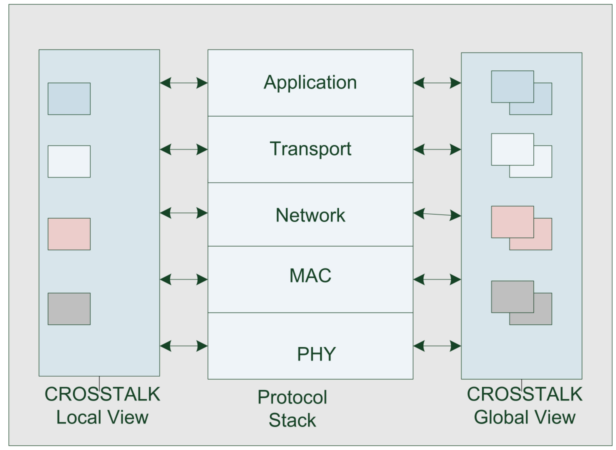

Fig. 11. CROSSTALK Cross-layer architecture

is high. However, the design involves changes to almost every protocol that uses context as well as providing the context. In addition to that, there exists an extra complexity in implementing TLs and POs. So, implementation is complex when the architecture has to be exploited with multiple concurrent adaptations. Also maintenance and management of product evolution is difficult. Further, TLs and POs add extra signaling overhead and latency to the context exchange mechanism.

Cross-Layer Decision Support Based on Global Knowledge-CrossTalk

A cross layer architecture called CrossTalk for decision support based on global knowledge is presented in [86]. CrossTalk enables mobile devices to establish the status of the mobile node as *local view* and relative status compared to global network conditions as *global view*. Local view is represented as the sum of local parameters such as battery level, SNR, location information and transmit-power. Global view is based on the metrics such as energy level, communication load and neighbor degree. The CrossTalk architecture consists of two data management entities to manage aforementioned local and global views. Adopted architectural details from [86] are shown in Figure 11. CrossTalk proposes local adaptations of the mobile device based on the global status. Further, the global view is encouraged to use whenever possible to have network wide accurate decisions.

CrossTalk proposes a comprehensive network wide decision mechanism. The architecture can coexist with the layered architecture because of the uninterrupted operation to the stack. However, CrossTalk does not address the local view in great detail for example how the local parameters are acquired by the local view management entity and how these are exchanged to interested protocols. Further, establishing a global view and data dissemination is costly and complex. Solution is less flexible in local adaptations and performance improvements because of the lack of support for local adaptations. Latency and overhead is high due to complex network wide data dissemination procedure. Local data accessibility and dissemination procedure is not addressed and information about modularity of signaling mechanism is not available.

Cross-layer Context Aware Architecture for Real-time Wireless Communication-(CA)2RW-Com

A cohesive and holistic cross-layer architecture called (CA)2RW-Com for real-time communication was proposed in [49], [50]. (CA)2RW-Com architectural details are illustrated in Figure 12.

ConEx [50], the context exchange mechanism of (CA)2RW-Com, composed of layer interfaces called LAYER_LENAs and LENA (Local Event Notification Agent). ConEx enables context exchange through subscription based event notifications. In addition to the context exchange, (CA)2RW-Com addresses other aspects of cross-layer context awareness such as context modeling (through context representation module), context acquisition and context management. (CA)2RW-Com defines situations using context and performance parameters. (CA)2RW-Com architecture enables context aware adaptations with minimal changes to the existing protocol stack using context acquisition through a protocol analyzer. (CA)2RW-Com separates non-cross-layer aware protocol stack operation from the cross-layer aware functionalities.

(CA)2RW-Com proposes a generic framework for context aware cross-layer interaction. (CA)2RW-Com can be easily enabled or disabled. Only cross-layer context aware entities subscribe to the architecture, so architecture ensures uninterrupted operation to non-cross-layer aware protocols and applications. Context acquisition through protocol analyzer ensures minimal changes to the protocol stack to publish context when an event occurs. So, (CA)2RW-Com has a higher degree of coexistence with the layered protocol stack. Context exchange module composed of LAYER_LENA and LENA through which (CA)2RW-Com preserves the modularity of the layered architecture. Moreover, the context exchange message overhead is minimized by the specifically defined light weighted message format. Further, the framework is flexible to support wide range of adaptations. Because the system can support single-layer, multi-layer adaptations in any to any layer fashion, scalability of the system is high. However, latency due to processing at each interface is higher compared to a direct signaling between non-adjacent layers. The design necessitates changes at mobile host only. However, context acquisition introduces some implementation complexity. So the overall implementation complexity is moderate. Maintenance of evolving protocols is also moderate. Latency of context exchange, design and implementation difficulties are costs to preserve modularity of the framework.

Local Server based Cross-Layer Coordination Framework

A cross-layer coordination framework consists of a local cross-layer coordination server and clients at each layer is suggested in [26]. Overview of the framework is shown in Figure 13. Non-adjacent layer interaction is done through the cross-layer server. Context delivery is performed in a way that, when an initiating layer wants to send a certain event to another target layer, the client of the initiating layer first sends event to the server, and then the server forwards it to the target layer. How the interested cross-layer protocols and applications can express interest for context is not addressed. A parameter repository is maintained at the server.

The framework preserves the modularity while maintaining a higher degree of flexibility by allowing interaction among non-adjacent layers. Since the cross-layer interactions are separated from the standard operational protocol stack coexistence of the framework with the layered stack is high. However, since the layers that support the parameters also need to be changed and all the adaptations are maintained at the layer client itself, the design complexity and maintainability of the framework is high. Since the parameters traverse through server-client are kept in a repository rather than notifying the interested layers as and when the event occurs, there is a high latency of signaling mechanism. Signaling overhead is low because the event structure composed of few fields.

Knowledge Plane based Cross-Layer Framework

A cross-layer architecture shown in Figure 14 is proposed in [70]. In this proposal, a knowledge plane database is maintained to encapsulate all layer independent information as well as the network-wide global view, which can be accessed by the layers. Two entities are used to maintain the local and global views. Each layer in the existing protocol stack has a contextor, which acts as the interface between the layer and the knowledge plane. The contextor is responsible for reading and updating the protocol data structures when it is necessary. The gossiping service built on top of existing TCP/UDP is used for gathering information from other nodes to generate the network-wide view at the node.

The architecture can coexist with the layered architecture with uninterrupted operation to the stack due to the separation of cross-layer operations from the non-cross-layer operations. Moreover, modularity of the system is high because it allows layer separation and preserves the modular functionality. Cross-layer interaction can be enabled at any layer, and solution can be extended to range of adaptations and optimizations through Kplane and contextors so the scalability is high. Since possible functionality for manipulating protocol data structures is built in to the contextors ensure that no modification is required to the existing protocol stack in framework implementation. However, maintenance and management of product evolution is very difficult due to the complexity. Further, this duplication requires synchronization between contextors and layer protocol functionalities. In addition to that, context exchange latency is high because of processing overhead at each contextor and KPlane. Further, latency of global data dissemination is high due to the message propagation and processing overhead of gossiping mechanism.

D. Comparison of generic cross-layer signaling mechanisms

Qualitative comparison of generic cross-layer architectures discussed in section III-C is show in Table II. The comparison considers the design attributes of each architecture including context exchange overhead, context exchange latency, scalability, design complexity, ability to coexist with the layered stack, modularity and maintainability which were defined in Section III-B. In addition, the number of adaptations tested in each architecture and whether they were simulations or real/testbeds was also recorded in comparison. The objective of including this is to give insights in to the ability to further extend the work, implement, compare or analyse.

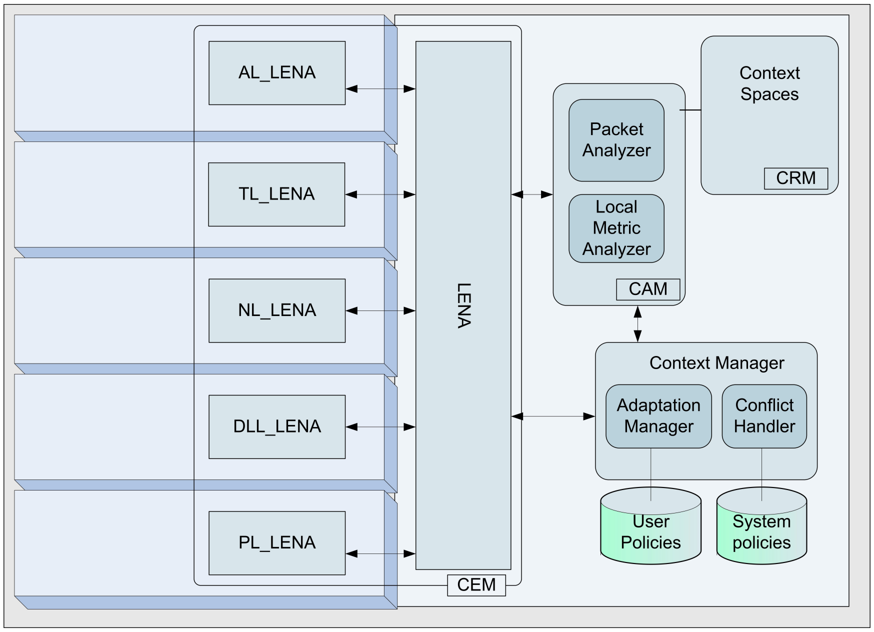

Fig. 12. (CA)2RW-Com Cross-layer architecture

TABLE II
COMPARISON OF GENERIC CROSS-LAYER MECHANISMS.

Mechanism	Context Exchange Overhead	Context Exchange Latency	Scalability	Design Complexity	Coexistence with layered stack	Modularity	Maintainability	Number of Adaptations Tested
ISP [88]	high	high	low	high	low	low	difficult	one simulation
ICMP [82]	high	high	low	moderate	yes	moderate	moderate	one real
WCI [42]	high	high	low	moderate	yes	high	easy	None
CLASS [84]	moderate	low	high	high	N/A	low	difficult	None
Planes [12]	N/A	N/A	low	high	yes	low	difficult	None
WIDENS [46]	high	high	low	high	yes	high	difficult	N/A
ECLAIR [68]	high	high	high	high	yes	high	difficult	one real
CROSSTALK [86]	high	high	low	high	yes	N/A	difficult	one real
(CA)2RW-Com [49]	low	high	high	moderate	yes	high	moderate	one simulation
LocalServer [26]	low	high	high	high	high	high	difficult	None
KPlanes [70]	high	high	high	high	yes	high	difficult	Two independent simulations

IV. Context Awareness and Parameter Classification

A. Context Awareness

Context aware studies which use context include context aware frameworks and pervasive computing applications. Some of the context aware frameworks are Context Broker Architecture [14], Context Mediated framework [52] and Context Toolkit [22]. Some of the pervasive computing applications are SenSay [77], Smart Kindergarten [78] and Active Campus [31].

A general definition of context for context aware computing domain is presented in [21]. "context is any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves".[2]

A definition of context awareness is also provided in [21]. *a system to be context-aware if it uses context to provide relevant*

[2]A. K. Dey, Understanding and using context, Personal Ubiquitous Computing., vol. 5, no. 1, 2001, pp.5

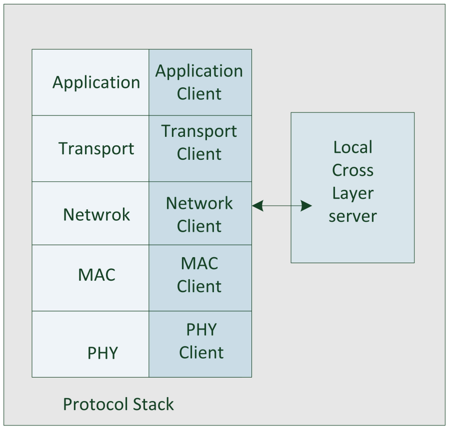

Fig. 13. Local Server based Cross-layer Coordination Framework

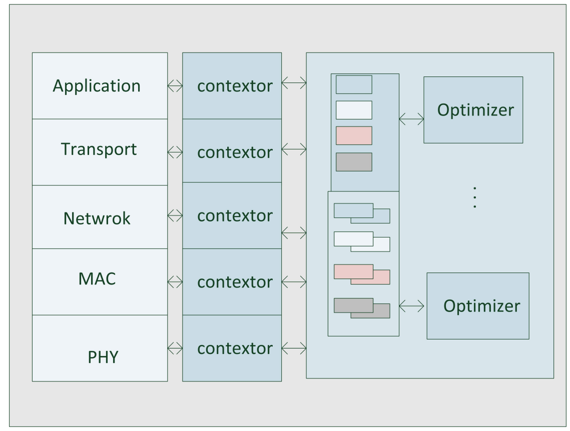

Fig. 14. Knowledge Plane based Cross-Layer Framework

information to the user, where relevancy depends on the user's task

Challenges in context aware computing, include uncertainty, diversity and complexity of context information. Research studies have been investigated important aspects of context aware-computing such as context discovery, context presentation, context execution and reasoning about context to address aforementioned challenges [41], [61], [63], [64].

Context Modeling: Context representation and modeling has been used in various domain specific requirements to describe context. Mark-up based models extend existing web standards such as XML [3] and RDF [4] to represent contextual information. Composite Capability/Preference Profiles (CC/PP) [5] is a data representation mark-up format based on RDF, which is proposed to describe user agent and proxy capabilities and preferences. The Comprehensive Structured Context Profiles (CSCP) context model which overcomes structural shortcoming of CC/PP is proposed in [34]. XML based context representation is proposed in [11]. XML is used to encode context configurations and values, and XML associated tree structure and XML schema are used to represent richer data and meta-data. Context modeling approach called Context Space which describes context and situations with spatial metaphors of state and space is presented in [60]. Context Space explicitly models context and situations rather than just representing specific contextual information.

More recently, comprehensive reviews on context aware computing are presented in [45] and [65]. The review and analysis on context-aware middleware systems presented in [45] considers the functions of undertaking context modelling, management, reasoning and provisioning. A survey presented in [65] focuses on context aware computing for Internet of Things.

B. Cross Layer Context Awareness

Section IV-A presented an overview of context-awareness in general. This section discusses the importance of context awareness in cross layer signaling and wireless networking.

[3]http://www.w3.org/XML/, Access Aug 2011
[4]http://www.w3.org/TR/1999/REC-rdf-syntax-19990222/ Access Aug 2011
[5]http://www.w3.org/TR/2001/WD-CCPP-struct-vocab-20010315/ Access Aug 2011

- Next generation computing is becoming increasingly ubiquitous. To facilitate cross-layer adaptations in such a pervasive system, the protocols and applications should be situation aware. Hence, context awareness is extremely important in cross-layer interactions in wireless networks.
- As proposed in [39] uncontrolled cross-layer interactions can lead to overall performance degradation. We argue that to investigate dependency relationships and conflicting interests of protocols, a detail analysis of context parameters used in each adaptation is vital. So, clear definition of context parameters used in specific adaptations and applications is necessary in order to facilitate control over multiple adaptations to avoid performance degradation of whole system.

Context parameters used in cross-layer context aware adaptations discussed in Section III-A and III-C are classified. Table III shows the classification of identified layer parameters corresponds to each layer adaptation.

To facilitate context awareness, it is necessary to investigate other aspects of context awareness, in addition to the signaling mechanisms (context exchange) addressed in most of cross-layer architectures. Generic mechanisms of context presentation and context acquisition are key aspects which are missing in most of the generic architectures proposed in literature for cross layer interactions.

C. Cross Layer Context Modelling

We use adaptive context [47] to model real-world cross-layer contextual adaptations. The adaptive context is used for further, context manipulation for example reasoning about context [61]. These context parameters are modeled using vectors as follows.

Let the application space R is the universe of discourse in terms of possible contextual data (which are network or local data) in the system. It is defined by a tuple whose members represent all possible context parameters and possible values for each context parameter.

Cross layer adaptive context is a combination of context parameters (context parameters exchanged across the layers) and performance parameters (context parameters used for performance measures of the adaptation). These parameters

TABLE III
CONTEXT PARAMETERS OF LAYER ADAPTATIONS

Adaptation	**Layer**	**Parameter**
Application Layer Adaptations		
QoS Control ([74], [83], [18], [40])	Application Layer	user application priorities, user QoS preferences (delay sensitivity, loss tolerance), source distortion, packet loss rate, video source coding, user satisfaction (MOS), PSNR
	Link Layer	packet Size
	Physical Layer	modulation, code rate, symbol rate
Packetization ([43], [85], [55], [53])	Application Layer	QoS (delay sensitivity)
	Data Link Layer	channel rate, multiple access, network access delay, error detection (retry limits, frame length, BER)
	Transport Layer	hybrid ARQ error control
	Physical Layer	modulation, antenna diversity, power delay profile, time delay profile, time delay speed, transmitter signal power, maximum adaptation frequency, battery power
Transport Layer Adaptations		
Mobility Adaptations ([51])	Network Layer	handover notifications
Congestion Control/Rate Control/ Error corrections ([19], [56], [76], [74], [18], [53])	Application Layer	service quality, source bit rate
	Transport Layer	congestion distortion, receiver window, timeout clock, congestion window, TCP/UDP header checksum, TCP/UDP header options, serial number of corrupted packet
	Network Layer	route data(route failures, route changes)
	Data Link Layer	SNR, BER, error coding, channel conditions (channel access delay, congestion)
Network Layer Adaptations		
Adaptive routing ([19], [89], [56], [74], [18], [58], [43], [23], [91], [7], [62], [13])	Application Layer	traffic type, delay bound, transmission delay jitter bound
	Network Layer	routing metrics, route outage probability, number of nodes in routes, network packet size(routing protocol), bit rate
	Data Link Layer	link outage probability, network congestion, packet delay, link state routing, average SNR, SNR threshold
	Physical Layer	battery power, min transmission power, path loss exponent, transmission range
Mobility Management ([9], [54])	Application Layer	application/user QoS requirements
	Data Link Layer	Link layer handover triggers
Data Link Layer Adaptations		
Scheduling and Adaptive Error Control ([19], [56], [71], [76], [74], [18], [40], [53])	Application Layer	service quality
	Network Layer	routing data (route failures, changes)
	Data Link Layer	SNR, link transmission rate, packet size/length, symbol rate, constellation size, error control system, channel conditions (packet loss, sequence number of packets), network delay, congestion(queue length, average link layer utilization), link BW, PER,RTT, Time slots, queue of packets per user, partial checksum
	Physical Layer	channel conditions (equalizer information -fading.), battery power
Channel/Rate adaptation ([74], [55], [23], [91], [62], [13])	Application Layer	transmission rate
	Data Link Layer	SNR, BER, error detection (retry limits, frame control), BW, link capacity, outage probability of links, link transmission rates
	Physical Layer	interference, SNR, noise, fading
Physical Layer Adaptations		
Adaptive Modulation/Transmission mode ([74], [18], [58], [83])	Application Layer	service quality
	Network Layer	routing data/traffic, network data rate
	Data Link Layer	SNR, payload data,
	physical Layer	mode, channel fading, channel code rate, modulation, bytes per symbol, BS-user gain, transmit power, SINR
Congestion Recognition	Physical Layer	load estimation intra-cell interference, Base station transmit power
Power Control ([56], [83], [85], [23], [7])	Data Link Layer	angle of arrival (AOA) of RTS, CTS, transmission rate
	Physical Layer	energy usage (CPU, network)

either static or dynamic form the adaptive context vector corresponding to a particular adaptation. These are defined based on the context definition presented in Section .

Context vector corresponds to a given adaptive context at time t v_t, can be represented as a vector consists of a set of adaptation parameters (ap) and set of performance parameters (pp).

Adaptive Context is shown in Equation 1.

$$V_t = \sum_{i=1}^{n} a_i ap_{xi}^t + \sum_{j=1}^{m} b_j pp_j^t \quad (1)$$

Where, a_i , b_j are scalars.
ap_{xi}^t is the i^{th} adaptation parameter at layer x at time t.
pp_j^t is the j^{th} performance parameter at time t.
So, adaptive context vector at time t, can be written as shown in Equation 2

$$V_t = a_1.ap_{11}^t ... + a_n.ap_{5n}^t + b_1.pp_1^t ... + b_m.pp_m^t \quad (2)$$

Reader may refer to [47] and [48] for further definitions and taxonomy for cross layer context modeling.

V. Open Research Challenges

Individual aspects of cross-layer interactions were widely studied in the literature. We identified following open research challenges to be addressed through a holistic and cohesive view of the system.

A. Challenges in Design Considerations

Performance related design considerations such as overhead and latency were taken in to account in some of the generic framework designs [84]. However, modularity and design complexity are not thoroughly addressed. It is crystal-clear that, supporting cross-layer interactions while providing full layered abstraction is impossible. But cross-layer interactions should minimize the violation to the layer modularity. Enabling context aware adaptations through cross-layer interactions while *preserving modularity* of the widely adapted layered protocol stack is still challenging because preserving modularity does not have a clear definition or measure. In addition to that, the design complexity was discussed in the literature [68]. However, providing a measure of how complex the design is on quantitative base in not addressed. So, the major challenge in following design guidelines such as preserving modularity and minimal design complexity is the absence of a common ground or standards to measure them. The only evaluation mechanism possible is the qualitative comparison. Hence, it is challenging to compare and evaluate frameworks based on the design criteria on an absolute quantitative measure. For example, [27] and [38] provide examples that quantify modularity in software engineering and engineering system disciplines consecutively.

B. Standardizing Generic Framework

Carefully designed, and well planned-framework, should be generic to support range of adaptations. Significant amount of effort and time is required developing the designed framework. The framework's ability to extend it to multiple local and global adaptations demonstrates the ability of the framework to standardize. It is necessary for cross-layer mechanisms and frameworks become standardized to improve the viability and for them to evolve in future.

Various generic architectures discussed above could lead/contribute to standardization process of a unified framework for cross-layer interactions in wireless networks. While achieving such a common standardization is far away of the road ahead, there are some examples for such standardization efforts. One such example is the Broadband Radio Access Network (BRAN) HiperLAN2. HiperLAN2 has been designed to achieve better performance of wireless LANs [24] through introduction of an efficient MAC frame, link adaptation and scheduling mechanisms. Convergence layer of HiperLAN 2 takes care of service dependent functionality between DLC and Network layer.

C. Scalability of Framework

Once a generic framework is achieved, it should support multiple adaptations. Almost none of the generic frameworks are tested or evaluated with more than one adaptation concurrently. Framework proposed in [70] was tested with more than one adaptation in simulation environment even though the adaptations are independent. It is necessary to deploy the frameworks through several concurrent adaptations to demonstrate the scalability.

D. Performance Analysis

Quantitative and quantitative analysis of all performance related attributes is important in cross-layer interactions. Comparative quantitative study should be carried out wherever possible. Cost associated with the mechanisms in terms of cost parameters such as overhead and latency should be analyzed over the performance improvements in terms of benefit parameters such as throughput enhancement, network capacity and packet loss reduction. Cost-benefit analysis of frameworks should show that performance improvements are significant enough and outweigh the associated costs. Performance analysis should address the impact on overall system as well as impact on overall network performance. While each an individual node in the network independently improves the performance through cross-layer adaptations, consequences on the overall network should also be monitored where applicable.

A good theoretical analysis of any proposed architecture can be derived based on [17]. This paper discusses the mathematical theory of network architectures. Each layer in the layered stack is viewed as a decomposed sub-problem and the interfaced are quantified as functions of the optimization variables which are coordinating the sub-problems [17]. It is argued that many existing network protocols can be reverse-engineered as implicitly solving some optimization-theoretic or game-theoretic problems. Also, by distributively solving generalized NUM formulations through decomposed subproblems, one can systematically generate layered protocol stacks. It also provides horizontal decomposition into disparate network elements and vertical decomposition into functional modules as well as standard techniques to tackle coupling and non-convexity used by researcher are discussed [17].

E. Concurrent Multiple Adaptations

When multiple adaptations are implemented concurrently, it may introduce various unintended consequences on the overall system.

Dependencies: As noted in [39], unintended functionalities due to dependencies of various interactions can cause performance degradation of overall system. So, interactions that depend on each other should be carefully managed. Holistic view of whole interactions should be available as a dependency graph which represents interactions between protocols based on associated context parameters.

Conflict: In addition to the dependencies of various adaptations another cautionary aspect in concurrent adaptations is the conflicting objectives. Two different adaptations may have conflicting interest on a parameter at a given time. Such conflicts should not be allowed at all. Further, as mentioned in [39], uncontrolled multiple interactions can get spaghetti-like protocol architecture hence such interactions should be avoided.

It is extremely important that interactions are controlled to handle conflicting adaptations and dependencies. Controlling interactions of multiple concurrent cross-layer adaptations is still an open research issue.

F. System Stability

As argued in [39], it is important to ensure the system stability when dependency relations are involved. As suggested in [39], such adaptations can benefit from time-scale separation, for the system to be stable. The concept is to make two entities control or use the same variable on different time scales. Further, it is an open research challenge to prove the stability for every closed loop in the dependency graph which has interactions at the same time scale.

G. Real System Evaluation

Some of the evaluations of the cross-layer frameworks proposed in the literature are implemented on network simulators. Limitations of simulators lead the researchers to evaluate on real-test beds. A real-world framework to evaluate cross-layer protocols for wireless multi-hop networks is implemented in [37]. It is proposed to use Embedded Sensor Board (ESB), a sensor network to test cross-layer protocols in real environment [37]. The software framework allows upper layers to implement cross-layer interactions through access to extended link layer and routing. However, these test-beds are designed for specific requirements and cannot be use to evaluate wide range of adaptations. Further, as noted in [92], modifications to WLAN adapters in test-beds that use IEEE 802.11 is a challenge because large parts of functionalities of the link layer are built closer to the proprietary hardware. So, building an efficient real system to experiment cross-layer design of wireless networks is still an open research issue.

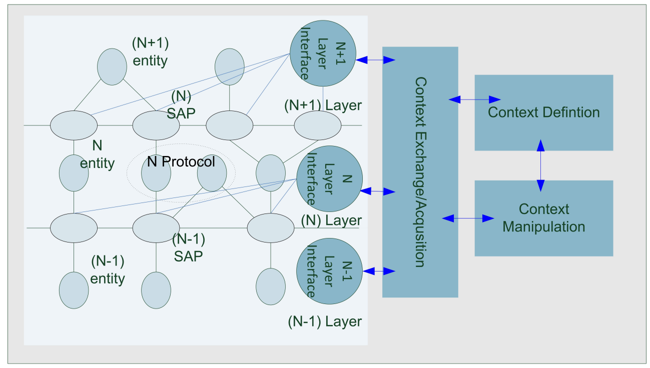

Fig. 15. Generic Reference Architecture for Cross-layer architecture

H. Context Awareness and Parameter Classification

Tremendous number of work has been done in specific cross-layer adaptations both single layer and joint multiple layer adaptations. Some of the selected single layer and multi-layer adaptations were discussed in Section III-A and generic frameworks were discussed in III-C. Most of the generic architectures address the context exchange and signaling mechanisms. Some studies [70], [82] analyze the context at various layers of the protocol stack relation to each adaptation. Very few studies [49], [82] address context acquisition. (CA)2RW-Com [49] architecture we propose addresses the context awareness in cross-layer signaling in great detail and proposed a generic context modeling mechanism. Generic context modeling can lead to identify dependency relationships as well. So there is a need of holistic view of context awareness and a generic framework to support context awareness including context representation, context acquisition, context exchange and context management in cross-layer design.

I. A Generic Reference Architecture for cross-layer interactions

We propose the reference architecture shown in Figure 15 as a generic architecture for cross-layer interactions. The generic architecture should facilitate cross-layer context definition, exchange and manipulation. Each layer has an interface for the context exchange module of the architecture in order to retain the modularity. Depending on the adaptation requirements the context acquisition can be centralised or part of context exchange [50]. Also, the context manipulation can be an external entity in case of joint multi-layer adaptations and part of the protocol/adaptive application in case of specific adaptations.

VI. CONCLUSION

Over the past years various research projects proved the fact that cross-layer design is a promising solution for efficiency in evolving wireless technologies. Along the line, some research studies identified the consequences and possible impacts of cross-layer design highlighting the cost of cross-layer design overhead to be paid to gain the performance benefits.

Existing cross-layer solutions mainly consider individual aspects of cross-layer interactions. Very few research projects present an integrated view on the cross-layer interaction enabled WLANs. We discussed considerations and design guidelines for generic cross-layer framework design based on cohesive analysis of the overall architecture. Further, we propose the importance of context awareness in cross-layer interactions which is an open research challenge. Our survey took a more holistic view hence identifies the following gaps in the body of knowledge in the area:

- A standardized set of design guidelines and design criteria is vital in generic cross-layer framework design. Qualitative and quantitative measures should be used to evaluate the framework design. Once a proper design for generic framework is accepted by standardization bodies, appropriate time and effort should be utilized to implement the framework. Hence, standardization of design guidelines and acceptance of adopted generic framework are equally important for cross-layer interactions to improve the viability and to enable evolution.
- Once the generic framework is widely accepted it is important to deploy the frameworks through multiple concurrent adaptations. Adaptations supported in the framework can be top-down, bottom-up, single-layer, joint multi-layer or in more generic form, any-to-any layer context aware adaptations.
- Once the framework is deployed through concurrent multiple adaptations the system stability should be studied. Handling dependency relationships and controlling conflicting adaptations are important in system stability to avoid unintended negative consequences on the overall system operation.
- Cost benefit analysis of the adaptations over the framework is important. The individual system-wide performance analysis is important. Similarly, whole network-wide performance analysis is critical.
- Defining clear cross-layer context parameters is a gap to be filled. Generic context modeling for cross-layer interactions can lay the basis to identify context dependencies hence control of multiple cross-layer interactions becomes possible. Other aspects of context awareness can enable effective situation aware cross-layer adaptations for future wireless networks.

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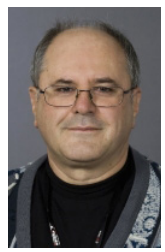

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