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Cross Layer Design in WMNs: Survey

Prof. Veena Kiragi[1]
Department of Computer Engineering.
Indira College of Engineering and Management,
Pune – India

Prof. Jambukeshwar Pujari[2]
Department of Information Technology.
K.I.T., College of Engineering,
Kolharpur – India

Abstract: Wireless mesh networks, as of late picked up a great deal of fame because of their rapid deployment and instant communication capabilities. The traditional layered-protocol architecture does not provide optimal performance for wireless mesh networks (WMNs). The method of optimization decomposition of the protocol stack can achieve optimal network performance. This method usually results in a clean-slate protocol architecture that is different from the protocol architecture of WMNs. Such a distinction really exhibits the requirement for a cross-layer design. Specific features pertaining to WMNs also show the need for cross-layer optimization across different protocol layers. In this paper, we discuss the need for cross-layer design in WMNs and the various challenges in cross-layer design.

Keywords: WMN, cross-layer design, protocol stack.

I. INTRODUCTION

Wireless Mesh Networks (WMNs)[1] are developing innovation and are gaining huge ground in the field of wireless networks in recent years. Mesh networks are capable of rapid deployment and reconfiguration and this gives those advantages like low up-front cost, simplicity of setting up a network, easy network maintenance, robustness (inherent fault tolerance against network failures), broadband capability and reliable service coverage. Their fame originates from the way that they are self-organized, self-configurable and easily adaptable to different traffic requirements and network changes.

Typically WMNs consist of mesh routers and mesh clients, where each node can operate both as host and router. Mesh routers for the most part have minimal mobility in a mesh network and form the backbone of WMNs. The clients could be either stationary or mobile and can form self organized ad hoc networks which can access services by relaying requests to wireless backbone network. In WMNs the communication is through radio nodes and utilize multi-hop relaying similar to an ad hoc wireless network.

Recently, a lot of research effort has been focused on multi-radio wireless mesh networks. Due to the relatively low cost of commodity wireless hardware such as radio interfaces based on IEEE 802.11 standards, it is now attainable to incorporate multiple radios on a single node. By working these interfaces on orthogonal channels, the limit of a Mesh Router can be fundamentally expanded, and it beats the restriction of half duplex operation of single-radio nodes. However, routing protocols must be designed to take advantage of the availability of multiple interfaces productively.

II. WMN(WIRELESS MESH NETWORKS): OVERVIEW

This section explains the basic idea of the Wireless Mesh Networks along with the need for the CROSS-LAYER DESIGN.

2.1 WMN ARCHITECTURE

There are three main types in the WMNs: i) Infrastructure, ii) Client and iii) Hybrid.

i) Infrastructure WMN: Here Mesh Clients gain access to each other or to the backhaul network through Mesh Routers. They are not actively involved in the routing and forwarding of packets. So, all Mesh Clients gain access to Mesh Routers via a single wireless hop.

ii) Client WMNs: Mesh Clients communicate with each other directly, without involving any Mesh Routers. So, Client WMN can be considered as a pure multi-hop mobile ad-hoc wireless network.

iii) Hybrid WMN: This combines the connectivity pattern of both the Infrastructure and Client WMNs as shown in the fig. 2.1. In this network, both the Mesh Clients and Mesh Routers are actively involved in the routing and forwarding of packets. Along with this, the Mesh Clients can also access the wireless backhaul network via multiple client hops.

Consider a typical scenario of Hybrid WMN, where it might be employed is, in emergency response systems and disaster recovery situations. Here, if traditional communication infrastructure might not be available, in such a situation, a hybrid WMN provides a so-called incident area network

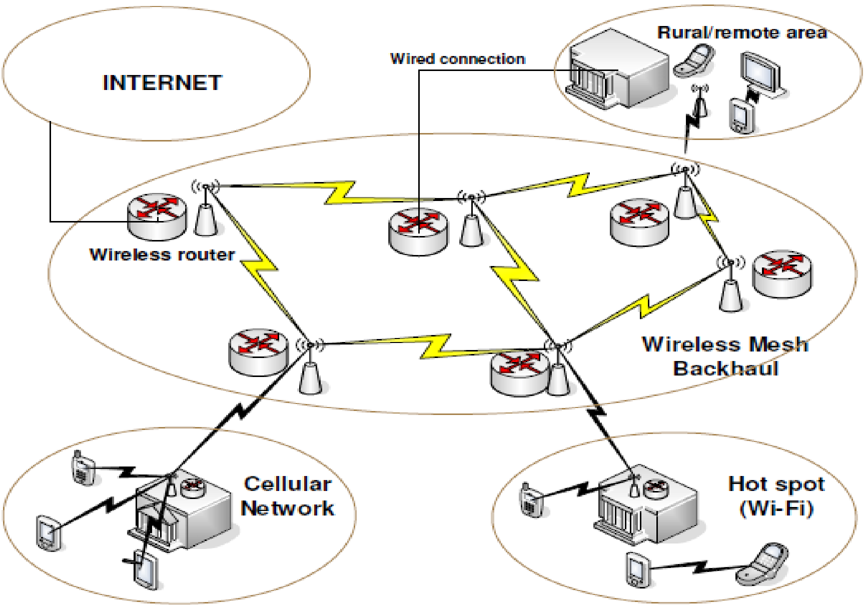

Fig 2.1 Typical wireless mesh network scenario [10]

2.2 APPLICATIONS OF WMN

1. One of the most popular WMN applications is providing broadband Internet access [2]. In this case, WMN routers are installed on the roofs of the clients and/or light poles within the coverage area of the WMN. Mobile Clients may roam while being handed over from one wireless router to another. The main advantage of WMNs over traditional broadband Internet (cable-modem and xDSL) access technologies is that the drastically reduced initial investment, deployment time, reliability and the coverage area especially in the areas with major obstructions like trees, high-rise buildings etc.

2. The WMNs provide support for applications that are not possible with other existing wireless networks such as cellular networks, wireless sensor networks, ad hoc networks etc. The possible applications include wireless broadband services, instant surveillance systems, community networking, intelligent transportation systems, high speed metropolitan area networks, transient networks in convention centers, disaster recovery systems and back-haul service for large-scale wireless sensor networks.

3. In WMNs, it is possible to cover the same area as of Wi-Fi. This uses less wireless routers, which makes the use of WMNs a convincing economical case [3]

4. Along with this, wireless mesh networks [11] provides benefits such as ease of installation, a high level of scalability in coverage area and capacity, cost effective deployments, network flexibility and self-configuration capabilities. These benefits enable the creation of faultless communication in underdeveloped rural areas.

III. CROSS LAYER DESIGN: NECESSITYAND CHALLENGES

This is a layered architecture [7] similar to that of the seven-layer Open Systems Interconnect (OSI) model. This architecture divides the overall networking task into layers and also defines a hierarchy of services to be provided by the individual layers. The services at each layer are realized by designing protocols for that particular layer. The architecture forbids direct communication between nonadjacent layers. Communication between adjacent layers is limited to procedure calls and responses. In the framework of reference layered architecture, the designer can design protocols in two ways.

i) In first method, protocols can be designed by following the rules of the reference architecture. That is designing protocols such that a higher-layer protocol only makes use of the services at the lower layers and is not concerned about the details of how the service is being provided. Here protocols would not need any interfaces that are not present in the reference architecture.

ii) Alternatively, protocols can be designed by violating the reference architecture. Violation of a layered architecture include allowing direct communication between protocols at non adjacent layers or sharing variables between layers, creating new interfaces between layers, redefining the layer boundaries. Designing of protocol at a layer is based on the details of how another layer is designed; joint tuning of parameters across layers, and so on. Such violation of a layered architecture is cross-layer design with respect to the reference architecture. And also violation of a layered architecture involves giving up the luxury of designing protocols at different layers independently. Protocols designed in such a way impose some conditions on the processing at other layer(s).

Direct signaling between nonadjacent layers is allowed in Cross Layer design [6]. It introduces light-weighted internal message format and standardized external message format. Figure 3.1, shows the design frame work. The light-weighted internal signaling messages only have local meanings. And a limited number of external signaling messages which are implemented by ICMP protocol might be exchanged between a mobile host and its access network. This design has two major advantages. i) It uses the unique active and direct signaling between any two random layers, and also in both directions. Because of this, it has the lowest propagation latency with high efficiency and flexibility. ii) There is clear cut distinction between internal and external messages. Hence it applies optimized or standardized form for internal or external signaling respectively.

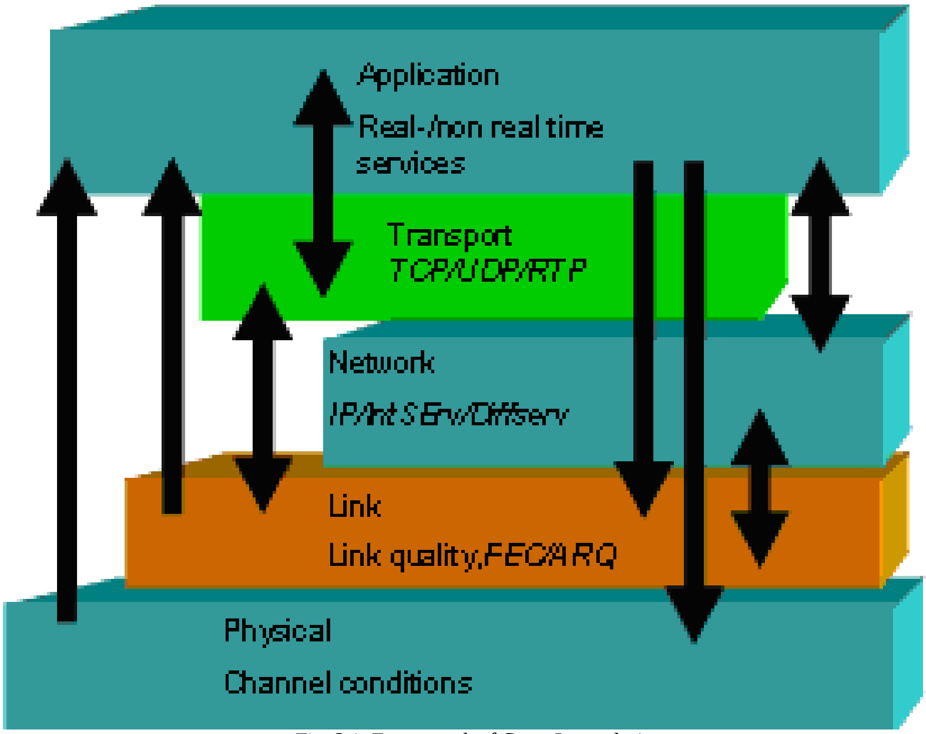

Fig. 3.1: Frame work of Cross Layer design

Cross-layer design [5] mainly refers to the designing of protocol by actively manipulating the dependence between protocol layers to obtain performance gain. But in layered design, the protocols at the different layers are designed independently.

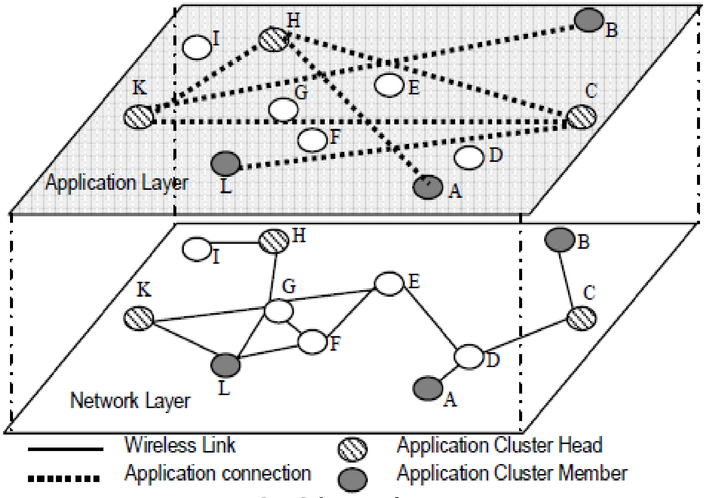

Fig. 3.2: Sub optimal routing

There are many cross-layer design proposals [7]. Here, we consider *how* the layers are coupled, that is what kind of architecture violation has taken place in a particular cross-layer design. The layered architecture can be violated in the following 4 basic ways:

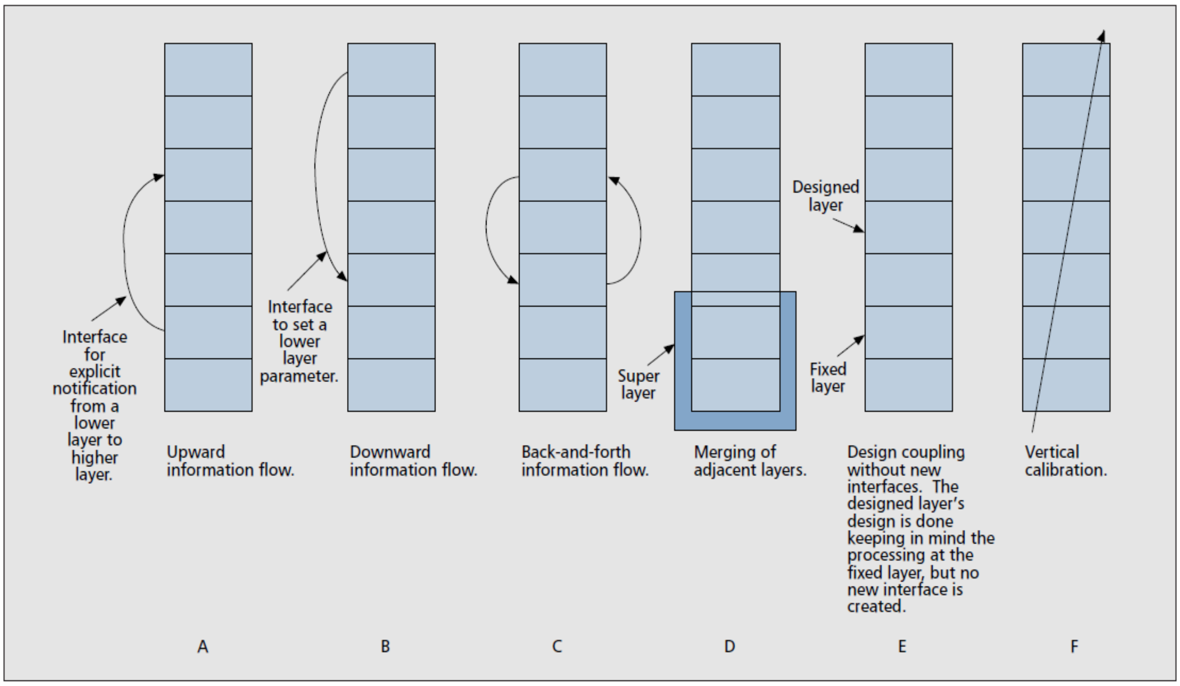

Fig. 3.3: Illustrating the different kinds of cross-layer design proposals. The rectangular boxes represent the protocol layers.

1. Creation of new interfaces (Figs. 3.3 a–c)

Several cross-layer designs require creation of new interfaces between the layers. At runtime, the new interfaces are used for information sharing between the layers. The creation of a new interface, which is not available in the layered architecture violates the basics of layered architecture.

- Upward: From lower layer(s) to a higher layer
- Downward: From higher layer(s) to a lower layer
- Back and forth: Iterative flow between two layers

2. Merging of adjacent layers (Fig. 3.3d)

Another way to do cross-layer design is to design two or more adjacent layers together to form a new super layer. The service delivered by the new *super layer* is the union of the services provided by the constituent layers. This does not require any new interfaces to be created in the stack.

3. Design coupling without new interfaces (Fig. 3.3e)

At design time coupling of two or more layers without creating any extra interfaces for information sharing at run time occurs.

4. Vertical calibration across layers (Fig. 3.3f)

This refers to adjusting of parameters that span across layers. The motivation is easy to understand. Here, the performance seen at the application level is a function of the parameters at all the layers below it. Hence, it is conceivable that joint tuning can help to achieve better performance than individual settings of parameters. Vertical calibration can be achieved in a static manner. This is done by setting parameters across the layers at design time with the optimization of some metric in mind. It can also be done dynamically at runtime, which emulates a flexible protocol stack that responds to variations in the channel, traffic, and overall network conditions. Static vertical calibration does not create significant consideration for implementations since the parameters can be adjusted once at design time and left untouched thereafter.

Dynamic vertical calibration, on the other hand, requires mechanisms to retrieve and update the values of the parameters being optimized from the different layers.

On the other hand, cross-layer design [10] through individual/some protocol layer design can significantly improve the network performance in two ways: loosely coupled and tightly coupled. In the loosely coupled cross-layer design, optimization is carried out without crossing layers but focusing on one protocol layer. Parameters in other protocol layers are taken into account by information exchange and deliveries from multiple layers to perform cross-layer design. With such information, the performance is improved because a better (more accurate or reliable) parameter is used, but the algorithm itself does not need a modification.

On the other hand, in the tightly coupled cross-layer design, merely information sharing between layers is not enough, but algorithms in different layers are optimized altogether as one optimization problem. Due to optimization execution across layers, better performance improvement can be achieved by both the loosely and the tightly coupled cross-layer design than only one of them is used. Furthermore, the advantage of adopting both schemes for cross-layer design is that it does not totally abandon the transparency between protocol layers.

3.1 MOTIVATION

Among layered-protocol design and cross-layer design, which has better optimized protocol performance in WMNs is still an on-going research topic [4]. In today's infrastructure-based networks such as telephony networks and the Interne, layered design has been very successful [5]. Protocols in one layer can be designed, enhanced, or even replaced without any impact on other protocol layers. However, such a methodology does not provide a mechanism for performance optimization between different protocol layers, which can significantly compromise network performance. This is particularly true for WMNs because it demands scalable network performance but is exposed to many challenging problems such as heterogeneous QoS constraints, multi hop wireless communications, and variable link capacity. The available MAC and routing protocols are not scalable; throughput drops significantly as the number of nodes or hops in WMNs increases. Thus, existing protocols need to be enhanced, revised or re-invented for WMNs.

Cross-layer design is particularly interesting for wireless networks that have some distinctive characteristics such as user mobility, frequent link failure, limited link capability and the limited battery powers of mobile devices. A cross-layer design may remove the duplicate functionality and data in layers. It may also optimize the parameters in each layer so that the performance in a single layer or in a whole system is enhanced. In a cross-layer paradigm, the joint optimization of control over two or more layers can yield significantly improved performance.

There are three main reasons to go for cross layer approach: [7]

- The unique problems created by wireless links,
- The possibility of opportunistic communication on wireless links, and
- The new modalities of communication offered by the wireless medium

3.2 CHALLENGES

Because cross-layer design has the potential to destroy the modularity and make the overall system fragile, it has to be designed very carefully[10]. Other important challenges during the design of cross-layered solution for WMNs is that the different operation time-scales between coding, scheduling and routing algorithms; especially when system performance estimations of different layers are considered. Moreover, since WMNs have to upkeep a wide variety of applications and services, because there are multi-constrained QoS requirements that have to be jointly satisfied by the cross-layer approach. For example, additive metrics (cost, delay, jitter, etc.), multiplicative metrics (packet-error-rate and path break probability), and concave metrics (throughput, etc.) have to be equally taken into account. Some more special type of challenges faced during the design of the cross layer protocol are listed below.

1) No clean-slate protocol architecture [4]: By optimization decomposition, a new protocol architecture that is quite different from the existing standard protocol stack can also result. The well-known TCP/IP protocol stack has been widely adopted for most applications of WMNs. Thus, how to make the layered-protocol architecture derived from optimization decomposition and the TCP/IP protocol stack match with each other is a technical challenge. It is highly possible that no match can be achieved in several cases. Thus, in order to further improve the network performance without abandoning the TCP/IP protocol stack, the cross-layer design must be designed.
2) Advanced physical-layer technologies: Many advanced physical-layer technologies have been adopted for WMNs in order to support applications that have high bandwidth demand. These technologies fall into several major categories.

a) Multi-rate-transmission technology: This is achieved by having multiple options of modulation, coding, and power-control schemes. Different transmission rate usually results in different transmission range and interference range. With multi-rate-transmission technology, the same physical layer can support a different transmission rate, depending on the link quality and the environment. In a single-hop wireless network, link-adaptation protocols, which are a type of simple cross-layer design schemes, can satisfy the need for maximizing throughput. In WMNs, however, merely the link adaptation is not enough, since links within multiple hops are related to each other. Thus, in WMNs, link adaptation becomes network-wide rather than a one-hop mechanism. Thus, link adaptation is inevitably cross-related to routing and topology control.

b) Advanced antenna technology: Directional antennas and the advance versions, such as smart antennas, can significantly reduce interference between nodes that are close to each other. Such techniques certainly increase the network capacity but also require additional algorithms in upper layers to coordinate the antenna direction or beam forming. In a single-hop wireless network, a control algorithm located in the MAC layer, i.e., MAC/physical cross-interaction is enough. However, in WMNs, routing needs to be considered together, since different beam forming or antenna direction impacts the routing path and *vice versa*. In other words, routing, MAC, and physical layers all need to work together. A more advanced antenna technology is multiple input and multiple output (MIMO). In a node using MIMO, advanced signaling processing technology is employed to achieve an optimal balance between link reliability and link capacity. MIMO on a point-to-point or point-to-multipoint setup has been well researched. However, taking advantage of MIMO in WMNs usually requires a network-wide-scheduling scheme.

c) Multichannel or multi-radio technology: Multichannel operation (either single- or multiple-radio) can significantly reduce the interference between nodes in a multi-hop network. To utilize such a technology, an additional algorithm (dynamic channel allocation) must be developed in the MAC layer. This algorithm also needs to be aware of the interference from external networks. Since varying channels in different hops potentially impact the optimal routing path that can be selected, both MAC and routing protocols must work together to take advantage of the multichannel technology. It should be noted that the above three classes of physical layer technologies are usually integrated, which further intensify the challenge in protocol design in upper layers. For example, the multi-rate transmission can happen in a physical layer using MIMO and multichannel operation. For a WMN with so many advanced physical-layer features, it is more challenging to re-optimize both MAC and routing protocols.

3) Imperfect MAC: MAC has always been a critical part in all wireless networks. Many solutions are available. However, none of them is perfect because of the following two major factors: 1) The wireless medium is always imperfect in nature, and 2) the MAC itself has no guaranteed performance. In the second factor, a typical example is CSMA/CA, which is a best effort protocol and cannot provide any guarantee for delay, collisions, etc. Such unpredictable performance of the MAC can severely limit the performance of a routing protocol. For example, routing messages may not be able to send out in a congested CSMA/CA-based WMN, which in turn impacts the capability of a routing protocol. This issue is even worse in WMNs, because the performance of MAC is not just a matter of single-hop networking but multi-hop. Research can be carried out to constantly improve the MAC protocols for WMNs. However, as a matter of fact, if routing is not taken into account, optimal performance can only be achieved locally. Consequently, in order to achieve the ultimate goal of perfect MAC, routing must be considered as an integral part of MAC. In this sense, MAC and routing protocols in WMNs are so closely related that they should be put together as two modules in one layer or even just one module in the same protocol layer. A typical example is the upcoming IEEE 802.11s standard for 802.11 WMNs, in which MAC and routing have been put together into the same MAC layer. However, we have also noticed that the optimal interactions between MAC and routing have not been exploited yet in IEEE 802.11s.
4) Mixed traffic types with heterogeneous QoS: WMNs are expected to support a large variety of services that consist of many traffic types with heterogeneous QoS requirements. In order to deliver such services in WMNs, transport layer, routing, and MAC protocols need to cooperate smoothly; otherwise, either service quality is not ensured or the network resources may be wasted. For example, it is always preferable to use separate transport layer protocols for VoIP, video, and data traffic. For VoIP and video traffic, finding a reliable routing path is obviously not the goal, since a path does not guarantee the quality of VoIP or video, no matter how reliable the path can be. Thus, finding a routing path must consider bandwidth allocation. This problem has been researched as a QoS-routing topic. However, when more advanced physical-layer technologies are considered, it becomes more than a QoS-routing problem and has to involve tight routing/MAC cross-layer design. For example, variation of bandwidth demand on a given routing path or change of a routing path can trigger reallocation of time slots, channels, antenna directions, etc., on all links related to the given routing path or *vice versa*.
5) Wireless Mesh Networks (WMNs) [11] have gained immense research interest. This sudden interest is because of WMNs can offer ubiquitous communication and seamless broad band applications. WMNs are hybrid networks considered to be variants of Wireless Ad Hoc Networks (WANETs) as they are built based on a mixture of fixed and mobile nodes interconnected via wireless links to form a multi-hop WANET. Thus, WMNs inherit most, if not all of the Multi-hop WANETs characteristics. There are numerous possible video streaming applications over multi-hop wireless mesh networks. Applications such as spontaneous videoconferencing in a place without wireless

infrastructure, Internet Protocol Television (IPTV), Video on Demand(VoD), video transmission on the battlefield, search and rescue operations, security and surveillance systems. However, there are still several research challenges that need to be addressed in all protocol layers for WMNs to support video streaming applications.

Based on the above analysis, cross-layer design is most challenging task for WMNs.

IV. Conclusion

We conclude that the cost obtained by using cross layer design is far cheaper than the layered architecture. Cross-layer design is mainly interesting for wireless networks which has some distinctive characteristics such as user mobility, frequent link failure, limited link capability and the limited battery powers of mobile devices. It also may remove the duplicate data and functionality in layers. It optimizes the parameters in each layer so as to increase the performance of a single layer or the whole system. But it has lots of challenges to overcome.

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