Protocol Design for Wireless Ad hoc Networks: The Cross-Layer Paradigm

Nabhendra Bisnik

***Abstract*— The wireless ad hoc networks are still in their infancy. The future of these networks would depend on the range of applications that they can efficiently support, which in turn would depend upon the underlying networking protocols. Since the wireless medium is fundamentally different from the wired medium, therefore the applicability of the OSI protocol stack to the wireless ad hoc networks needs to carefully evaluated and possibly a completely different architecture may be more suitable for wireless protocols. Recently there has been a lot of studies which show that cross-layer design is more suitable for wireless networks than the OSI stack model. In this study we evaluate the pros and cons of cross-layer design approach. We conclude that in general cross-layer approach must be cautiously used while designing wireless protocols. However stand alone, mission critical wireless networks may employ cross layer design to improve reliability and optimize performance.**

I. Introduction

The wireless ad hoc network is a collection of wireless nodes that communicate with each other without any established infrastructure and centralized control. The wireless nodes may be stationary or mobile. If the source and destination are not within each others communication range then the packets are forwarded to the destination by intermediate nodes. So each node may be a source, destination and relay of packets. The wireless ad hoc networks thus have a peer-to-peer communication model with control and routing functionalities distributed over all the nodes.

Wireless ad hoc networks have some distinct advantages over wired networks [4]. Wireless ad hoc networks are rapidly deployable, thus suitable for task of disaster management. Their distributed nature and node redundancy makes them fault resilient. They can also be easily tailored to specific applications, such as data gathering in remote and hostile environments. Some of the other potential applications for wireless ad hoc networks are wireless Internet access, home networks, device networks, sensor networks and distributed control systems [1].

[1]Please refer to [4] for details of the applications and the technologies involved

The wireless ad hoc networks are however plagued by variable link quality, time varying topology, contention for the channel and power constraints. At the same time the wireless medium allows modalities (such as accumulative routing, cooperative interference cancellation etc.) that are non existent in the wired networks. Therefore the issue of protocol design for wireless networks requires a serious deliberation on possible approaches before blindly adopting the open system interconnections (OSI) model for the protocol stack. The cross layer approach is perceived as one of the efficient solutions for designing protocols for the wireless networks. The cross layer design aims to achieve adaptivity and optimal performance by allowing sharing of information across several layers. However several concerns have been raised regarding the flexibility, inter-operateability, proliferation and even the performance of the cross layer design [5]. In this study we discuss the cross layer approach of protocol design for wireless networks. We present arguments in favor of and against the cross layer design. We briefly discuss some proposals that make aggressive use of cross layer design in order to gain performance. We also present a detailed discussion on design of protocols for transmit power control that adopt a more cautionary approach towards cross layer design.

The rest of this paper is organized as follows. In Section II, we present the design motivation and principles behind cross layer design. Section III presents several proposals that make aggressive use of cross layer design in order to adapt and optimize the performance of wireless networks. In section IV we backtrack a little on the optimistic course of the possibilities offered by cross layer design in order to discuss the disadvantages it offers and why a cautionary approach is more suitable. Section V presents a detailed discussion on the design of protocols for transmit power control in wireless networks. Section VI concludes the paper.

II. Why cross layer design makes sense

In this section we first discuss how the wireless networks differ from the wired networks. We then present the principles of cross layer design and the advantages it offers over the traditional OSI model.

A. Characteristics of wireless ad hoc networks

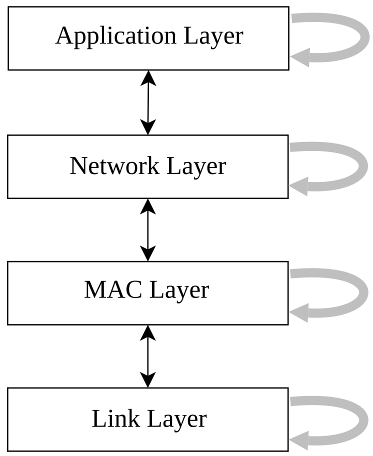
In this subsection we discuss the characteristics of wireless networks that make them fundamentally different from wired networks. We also elaborate how the characteristics effect various layers of the protocol stack.

1) *Link connectivity:* The concept of a link in wireless ad hoc networks is intrinsically different from that in the wired world. In the wired world the link connectivity is a binary decision, i.e. a link exists between two nodes if and only if they are connected by a physical medium like copper wireless, optical fiber, coaxial cable etc. However in wireless ad hoc networks a node can theoretically communicate with any other node at a rate that depends upon the signal-to-interference-plus-noise ratio (*SINR*) at the receiver and coding scheme used by the transmitter. So theoretically a "link" exists between any pair of nodes. The link SINR varies randomly, both temporally and spatially, due to the transmission distances, propagation environment and the interference caused by the transmission of interfering nodes. Because of the changing SINR, the feasible data and error rates over wireless links vary significantly over time.
   Variable link quality effects lead to unpredictable packet errors causing the packets to be dropped, which may effect various layers. The MAC layer may assume that the packet drop is caused by collision and therefore may increase its backoff although the channel may be free. This leads to large packet delays. The routing updates may be lost due to changing link qualities and therefore leading to constant change in the topology of the network as perceived by the network layer. This may cause large number of routing updates thus increasing the routing overhead. At the transport layer the packet drops may be attributed to congestion leading to decrease in throughput.
2) *Medium access control:* The wireless channel is inherently a broadcast medium. The sharing of the wireless channel among contending nodes is governed by the medium access control (MAC) protocols. The problem of medium access is common to the wired LANs. Random access MAC protocols are most popular in both wired (CSMA/CD) and wireless (CSMA/CA) domains because of their efficiency, distributed implementation and fault resilience. However the problem of medium access in wireless networks is complicated by the *hidden* and *exposed* terminal problems. The end-to-end delay and throughput depends highly on the medium access control protocols. Thus the fulfillment of the QoS requirement of a application depends on the performance of the MAC protocol.
3) *Power control:* By sufficiently increasing the transmit power a node may be able to communicate reliably with any other node using just one hop. In other words the quality of any wireless link may be arbitrarily improved by simply increasing the transmit power. Also any data rate may be supported on a wireless link by sufficiently increasing the power. Thus the topology of the network as perceived by the network layer is dependent on the power level of the nodes. Also with the increase in transmission power the number nodes effected by the transmission increases, thus effecting the MAC layer. The problem of protocol design for power control would be studied in depth in Section V.
4) *Mobility:* The nodes belonging to a wireless ad hoc networks may be mobile. Some examples of such nodes are hand held devices that may be carried around, devices attached to moving vehicles and devices attached to sensing robots. Mobility affects various layers of the protocol stack. At the link layer mobility governs how rapidly the link characteristics vary with time. At the MAC layer mobility governs how long the measurements regarding channel state and interference remain valid. Also mobility leads to change in network topology and thus governs the performance of the routing protocols.

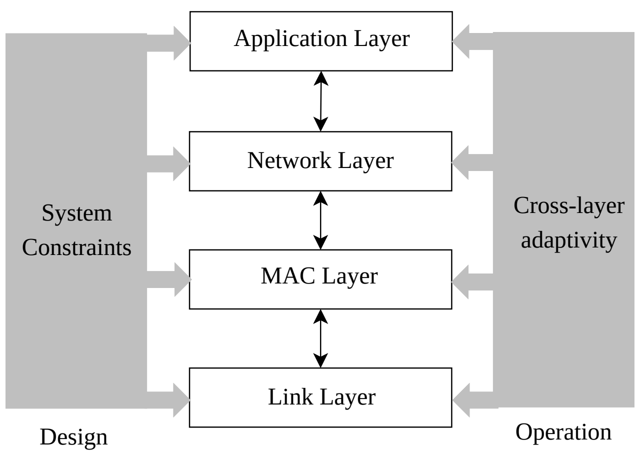
Compared to the wired networks the degree of variability of the state of wireless networks is quite high. Also the performance of the network, in terms of delay and throughput, is highly dependent upon the state of the network. The effects of the state of a wireless network is spread across several layers. Thus in order to meet the requirements of the application despite variable link state, network topology and power levels, it is important that the layers coordinate and adapt to the change in network state.

B. Cross layer design principle

One of the major components in the success of the Internet is the layered open system interconnection (OSI) architecture. The modularity achieved through layering leads to better understanding of the abstract functionality of layers and thus enables better understanding of the overall system. This led to rapid growth in the development of number of applications that drive the Internet. The fact that the same lower layers may be



(a) OSI model.



(b) Cross layer model.

Fig. 1. The OSI and cross layer model differ in both operation and philosophy.

reused for every application decreases the development cost of the application and enhances the utility of the network architecture. Layering simplifies network design and leads to robust scalable protocols in the internet.

Layering suffers from sub-optimality and inflexibility. Layering is suboptimal because each layer has insufficient information about the network since it does not allow the sharing of information among the layers. The interface between the layers are static and independent of individual network constraints and applications. Layering is inflexible because the developer of a new application has to solely on the functionality of the lower layers. According to the discussion presented in the previous subsection the layers in a wireless network must coordinate and adapt with the change in the state of the wireless network. This is the motivation behind the cross layer paradigm for protocol design in wireless networks.

The cross layer design of protocol stack enables layers to exchange state information in order to adapt and optimize the performance of the network. The difference between the layered architecture and the cross layer architecture is illustrated in figure II-B. The sharing of information enables each layer to have a global picture of the constraints and characteristics of the network, leads to better coordinations and enables them to take decisions that would jointly optimize the performance of the network. The cross layer principle further requires that the protocols must not be developed in isolation but in a integrated and hierarchical framework so as to take advantage of the interdependencies between the protocols. These interdependencies are related to the adaptivity at each layer, system constraints and requirements of the application [4].

In a cross layer architecture, MAC layer may adapt its scheduling based on the link quality and interference such that the performance constraints of the application are satisfied. Thus MAC layer needs to have information about the link characteristics from the link (lower) layer and the performance constraints from the application (upper) layer. Similarly a adaptive cross layer routing protocol may choose the routes based on the information about the link characteristics and MAC scheduling policy in order to meeting performance requirement.

It is important to understand that in order to adapt to a change in the network a layer must first try local adaptation and inform the upper layer about the change only if the local adaptation does not work. This because the time-scale of changes at lower levels is much lower than the time-scale of changes at the upper layers. For example, the SINR of a link may change much rapidly than the position of a node. So when the quality of a link degrades the link layer must first try to adapt to the change, possibly by increasing the transmit power or using better coding. This would temporarily solve the problem if the change in SINR is due to a random fluctuation and the SINR of the link would later be restored. However if the SINR of the link does not improve for a long time then the link layer realizes that this degradation may be due to a change of the topology (the other node might have moved away), so it informs the network layer that something has gone wrong with the link. The network layer then recalculates the routes using this information.

According to [4], the main issues that need to be considered while designing a cross layer protocol stack are:

- What information should be exchanged across protocol layers and how should that information be adapted to?
- How should the global system constraints and characteristics be factored into the protocol designs at each layer?

III. Proposals involving cross layer design

In the previous section we emphasized the importance of cross layer design and presented broad principles behind the cross layer design. In this section we present several proposal that use cross layer design in order to improve the performance of wireless networks.

A. Design of TCP over wireless

TCP is the default transport layer protocol for reliable end-to-end delivery of packets in wired networks. In addition to reliable delivery TCP is also responsible for the task of congestion control. The TCP executes congestion control in the following manner. The congestion in the network leads to overflow of queues at the routers which leads to packet drops. The TCP at the receiver end makes the TCP at the sender end aware of the packet loss by sending duplicate ACKs. On receiving three duplicate ACKs, the sender reduces (halves) its congestion window and enters the congestion avoidance phase. In other words TCP attributes any packet loss to congestion in the network and reduces transmission rate. This approach is effective in wired networks since the probability of packet loss due to bit errors is negligible. However in the wireless networks the probability packet loss due to bit errors is non negligible. If the traditional version of TCP is used in wireless networks then the packet loss due to bit error would substantially decrease the throughput.

There are two popular approaches for improving the performance of TCP in wireless networks: (i) Link layer approach [1] and (ii) Explicit congestion notification (ECN) [3]. In the former approach, link layer coding and ARQ scheme is used to retransmit packets that are lost due to variation in link state. This strategy works because the time required for recovering from packet error at the link layer is much smaller than the time in which TCP receives feedback about the packet. Still some duplicate ACKs may reach the TCP sender and cause reduction in throughput. The latter approach is based on addition of ECN bit in the TCP header. Whenever there is congestion at a router, the router sets the ECN bit in the TCP header of the packet (referred to as *marking packets*). When the marked packet reaches the destination, the destination becomes aware of the congestion in the network. The destination then explicitly informs source of the congestion so that it may reduce its transmission rate.

B. Joint physical-MAC layer design of the broadcast protocol [7]

Each node in a wireless ad hoc network periodically issues broadcast messages in order to inform its neighbors about its presence and also for discovering and updating routes. The efficient exchange of such broadcast messages is critical to the performance of a wireless ad hoc network. The broadcast messages are vulnerable to collision since they are not preceded by virtual channel sense and exchange of channel reservation messages (e.g. RTS-CTS messages in IEEE 802.11) [2]. The situation is further exacerbated if a broadcast message issued by a node triggers broadcast messages from its neighbors. This scenario is common to route request and routing update broadcast packets and is referred to as the *broadcast storm problem*.

A broadcast protocol based on physical-MAC cross layer design is proposed in [7]. The protocol, referred to as *FF-NDMA* (feedback-free network assisted diversity multiple access), provides higher capacity to exchange information among neighbors by exploiting the signal separation principles. The basic idea behind FF-NDMA is that if k broadcast messages are involved in a collision then k simultaneous transmissions of those messages are enough to decode each message. Such deduction of messages from multiple retransmissions of the same set of messages is referred to as *retransmission combining*.

The FF-NDMA protocol may described as follows. The multi access scheme is time slotted. A time slot in each frame is allocated for broadcasting messages. This subset of time slots is defined as the *broadcast channel*. Retransmission combining is possible if a receiving node detects collision of the same neighbors during as many time slots as the number of collided transmissions. In order to achieve this the broadcast channel is further divided into *contention periods* of length R slots. A node starts transmitting a broadcast message at the beginning of the contention period and retransmits it during each of the remaining slots of the contention period. If collision occurs at some node then the MAC layer detects the collision during the first slot and informs the link layer. The link layer then accumulates the information for the whole contention period. If number of colliding messages during a contention period is less than R then each message can thus be successfully decoded by the receiver. This improves the throughput capacity of broadcast information. The increase in the broadcast capacity is achieved at the cost of enlarging transmission time of each message from 1 to R slots. The performance of the protocol may be enhanced by optimizing the choice of R according the network parameters.

We present brief theoretical overview of the retransmission combining technique. Suppose k broadcast messages collide at a node. The received signal in a contention period of length R slots may be arranged in a matrix form in the following manner.

$$\begin{bmatrix} y_1 \\ \vdots \\ y_R \end{bmatrix} = \begin{bmatrix} A_{11} & \dots & A_{1k} \\ \vdots & \ddots & \vdots \\ A_{R1} & \dots & A_{Rk} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_k \end{bmatrix} + \begin{bmatrix} w_1 \\ \vdots \\ w_R \end{bmatrix} \tag{1}$$

where x_i is the message transmitted by the i^{th} user. y_j and w_j are the received signal and noise samples in the j^{th} slot of the contention period. The (j, i) element of the matrix A (A_{ji}) is the received signal amplitude of user i during slot j, as a result of combination of transmit power and propagation of channel loss. The separation of messages of each user is possible if the matrix A has full column rank. Since each entry of matrix A, A_{ji}, is governed by a continuous random process, the probability of the rank of A being less than k is zero. Thus each of the messages may be accurately reconstructed accurately as long as number of colliding messages is less than the length of contention period ($k \leq R$). Mechanisms for uniquely identifying each packet in a contention period and estimating the component of matrix A are also presented in [7].

C. Joint physical-MAC layer design for networks under Rayleigh fading [8]

The wireless channel is characterized by random time varying fading which dictates the SINR of the received signal. If the channel is in the state of deep fade then the SINR of received packet is very low and the receiver is not able to decode the message correctly. Thus the packet has to be dropped by the receiver although no collision had occurred. In a layered protocol stack the upper layers are unaware about the state of the wireless channel. As a result a node may keep on transmitting packets while the channel is in *bad* state. This would not only waste the resources of the transmitter but also cause needless interference at the neighboring nodes.

In [8], a cross layer design is proposed where the MAC layer predicts the state of the channel in order to make sure that that nodes do not transmit when the state of the channel is bad. The authors present a method for predicting the future state of a wireless channel under Rayleigh fading. The prediction is based upon an analytical model of Rayleigh fading channel and utilizes the past signal strength measurements. If the MAC layer predicts that the state of the channel is good then it defers transmission. The prediction model for Rayleigh fading channel is incorporated with a Markovian model for IEEE 802.11 MAC in order to analyze the performance of the proposed approach.

The predictability of Rayleigh fading channel is used to improve performance of the network in the following manner. The node at the receiving end observes the power levels of each received transmission from the receiver. Based on these measurements the receiver predicts whether the channel would be in good or bad state during the next transmission. If the receiver predicts that the state of the channel is going to be bad then it informs the sender about the fade and stops transmission of any reply packets to the sender. The receiver may inform the sender about the imminent fade by setting a flag in the ACK or CTS packet that it transmits to the sender. When the sender receives this notification then it immediately halts the transmission, calculates the expected fade duration and schedules future transmissions accordingly. The network allocation vector (NAV) at the neighbors is also updated when they overhear a CTS or ACK whose flag bit is marked. The simulation results presented in [8] indicate the cross-layer implementation performs better than the layer implementation in terms of received signal strength, throughput and fraction of packets dropped.

D. Cross-layer approach for network planning [9]

In [9], the network planning problem is modeled as the problem of allocating physical and medium access layer resources to minimize a cost function while fulfilling certain end-to-end communication demands. The demands in a set of wireless nodes, represented by V_o, are modeled as a collection of multicast sessions of the form $\Sigma_m \equiv \langle s^m, T^m, r^m \rangle$, $s^m \in V_o$, $T^m \subseteq V_o$, $r^m > 0$, $m = 1, \dots, M$ where in each multicast session Σ_m, a source s^m transmits data to a set of destination nodes T^m at a rate r^m bits/second. The allocation of resources is modeled as a timesharing within a collection of all possible physical layer states. The aim of the resource allocation is to minimize aggregate congestion and power consumption.

An *elementary capacity graph* is defined as a capacity graph thats represents a physical layer state, corresponding to an arrangement of concurrently active links between between neighbors. The MAC layer is abstracted by a set of all possible time sharing between the capacity graphs. Using this representation of MAC layer, the network layer maps the end-to-end traffic demands into link by link flow. The iterative cross-layer optimization proposed in [9] alternates between: (i) heuristically selecting a manageable collection of elementary graphs and (ii) jointly optimizing the allocation of resources and flow assignment in order to minimize congestion and power consumption.

More precisely, the method proposed in [9] may be described as follows. At the physical layer the network operates in many different physical states, each corresponding to an elementary capacity graph. The link layer presents networks layer a set of composite capacity graphs obtained by timesharing between different physical states. The timesharing of physical states leads to convex combination of elementary capacity graphs. The network layer utilizes the capacity graph to transform end-to-end traffic to link-by-link traffic. A cross layer optimization is achieved by integrating the above components. The performance of the proposed method is compared with the performance of layered protocols. It is observed that the cross-layered strategy out performs the layered approach. However algorithm for cross-layer optimization presented in [9] is centralized and therefore may not be directly implemented in a wireless ad hoc networks. Still it provides a nice insight into how sharing of information allows optimization of performance.

IV. Cross layer design: Is it worth applying it

In the previous sections we discussed the advantages offered by the cross-layer design and presented some proposals that use cross layer design. We argued that the layered protocol stack is suboptimal and that we must exploit the enormous opportunities offered by wireless communication by enabling the sharing of information across various layers of protocol stack in wireless networks. However it is pertinent to study this line of thinking in light of the goals that the designers of layered protocol stack aimed to achieve. In this section we discuss that why should the cross-layer design be approached in a cautious manner. We begin the discussion by highlighting the fundamental advantages offered by a layered architecture. We then discuss some of the pitfalls of the cross-layer design approach.

The layered architecture is not unique to the network protocol stack but is common to many popular systems that have withstood the test of time. The main advantage achieved by layering is the modularity and re-usability. Modularity implies that each layer may be developed or upgraded independent of other layers. Reusability allows sharing of lower layers by several instances of upper layers and thus reducing the cost of development and deployment of the system. This leads to a rapid proliferation of the layered systems. Although the layered architecture may not be optimal in the theoretical sense, the performance enhancement that it guarantees is the longevity of the system and low implementation costs. The examples of such layered architecture are [5]:

1) *The von Neumann architecture*: The von Neumann architecture is at the heart of most computer systems. It classifies the computer system into independent functional units (layers) that are: memory unit, control unit, arithmetic and logical unit and the input-output unit. The architecture make it possible that hardware and software for the computer systems may be developed independently. This is one of the major reasons behind the rapid proliferation of computer systems.
2) *Source-channel separation and digital system architecture*: In his seminal work on information theory, Shannon proved that the layers of source compression (source coding) and coding for reliable transmission over wireless channel (channel coding) may be implemented separately and independently. This implied that each new source of information (and the associated source encoder/decoder) may simply reuse the existing channel encoders/decoders, thus simplifying the implementation. In the same way new (more efficient) channel encoders/decoders may be designed without worrying about the sources that would be using the channel. This architecture has has fueled rapid development and proliferation of digital communication systems.
3) *The OSI architecture for networking*: The OSI architecture and its impact on development and proliferation of computer networks has been sufficiently discussed in this study.

The historical evidence thus seems to support layered design architectures. We now discuss some of the possible technical and economical disadvantages of cross layer design.

1) *Cost of development*: The aim of cross layer design is to adapt according to the network state so as to optimize the performance of the applications. So actions of the protocols are highly dependent on the application that the network is designed to support. If the demands of two applications or environments of two instances of wireless network are radically different then each of them would require a separate set of protocols. Thus the cross layers would have to be hand crafted for each application and network scenario. For example consider two networks N_1 and N_2. Suppose that in N_1 the nodes are battery operated while in

N_2 the nodes have infinite source of power (e.g. connected to electrical socket or operated on solar power). So in N_1 one of the objectives of the optimization would be consume minimum energy, while in N_2 this would not be valid. Although the protocol set of N_1 would work fine in N_2 also but then this again lead to suboptimal performance in N_2, to counter which the cross layer design was developed in the first place. So hand crafting of protocols for each application and network would lead to high deployment costs and delays.

2) *Performance vs. longevity*: The most popular argument in favor of sharing information among layers is that it leads to optimal performance. However such a gain in performance is of a short sighted nature. This is because the technologies at each layer (e.g. capabilities of MAC cards, coding schemes at link layer etc) change rapidly. So every change of technology the nature of information that is shared and the actions that are taken would need to be changed. This is against the principle of longevity which is considered an essential feature of any design. If we include the weight of longevity and cost while evaluating the over all performance of an architecture then the layered architecture may as well outperform the architectures that make aggressive use of cross-layer approach.
3) *Interaction and unintended consequences*: The layered architecture allows limited and controlled interactions between the layers such that the job of designing or modifying a protocol at any level is simplified. A cross layered approach leads to many dependencies between various layers. The designer of a new protocol in a cross layer system has take to understand and take into account the interaction of various layers. In spite of a good understanding a new protocol may lead to unintended consequences due to the presence of multiple adaptation loops. Such interactions need to studied using dependency graphs. Thus design of a protocol in a cross layer stack is much more challenging than the task of designing such protocol in layered stack.
4) *Stability*: As already mentioned that a cross layer design leads to several adaptation loops. The complex interaction of these loops may endanger the stability of the system.

Although cross layer design offers tremendous opportunities but at the same time it has several critical disadvantages. These disadvantages may hinder the proliferation of wireless networks. The cross-layer approach should thus be used with caution. There are many functionalities, like transmit power control and channel state estimation, that are typical of wireless networks and require a cross layer approach. In such cases where the cross layer design is necessary it should be made sure that the implementation is not very aggressive (i.e. does not rely too much on information exchanged among several layers). The placement of functions and the nature of the information exchanged between the layers must be kept minimum and must be critically analyzed. In the next section we discuss the implementation of transmit power control protocols in wireless ad hoc networks that use the similar approach.

V. Design of protocols for transmit power control

Transmit power control refers to the problem of selecting appropriate power level for transmission of each packet. Transmit power control is an important problem in wireless ad hoc networks because of various reasons. Most of the mobile ad hoc networks have battery powered nodes, so lifetime of network depends on the power that a node consumes for transmitting packets. Also the SINR at a node depends upon the transmit power levels of the neighboring nodes. Transmit power affects almost all layers in the protocol stack. Thus transmit power control is a prototypical example of cross layer design problem. In this section we study the design of transmit power control algorithms. We discuss how transmit power control effects various levels and extract basic design principles of power control. We also discuss some of the power control algorithms discussed in [6].

A. *Effect of transmit power control across several layers*

At the link level the transmit power at a node and its neighbors effects the SINR at the receiver and thus dictates the capacity of a link. Also transmit power control may lead to unidirectional links. Suppose node a uses higher transmit power than node b then $b \to a$ may not exists while $a \to b$ may exist. Unidirectional nature of wireless link has a major impact on the performance of the protocols of OSI model.

At the MAC layer the transmit power governs the nodes whose transmissions would be sensed by a nodes and therefore force it to defer its transmission. This governs the capacity and congestion in the network. Also the MAC protocols of OSI stack depend on the bidirectionality of the links. For example, IEEE 802.11 MAC assumes that the receiver is able to transmit CTS and ACK packets to the sender.

$P_{Rx_{elec}}$	The power consumed in receiver electronics for processing
$P_{Tx_{elec}}$	The power consumed in transmitter electronics for processing
$P_{Tx_{Rad}}$	The power consumed by the power amplifier in the transmitter for transmitting the packet at power level p
P_{Idle}	The power consumed when the radio is on but no signal is being received
P_{Sleep}	The power consumed when the radio is turned off

TABLE I
COMPONENTS OF POWER CONSUMPTION IN A WIRELESS CARD.

The transmit power controls the transmission range of a node and thus governs which nodes are the neighbors of the node. This effects the topology of the network and thus the network layer. Also most of the routing protocols belonging to the OSI stack rely on bidirectionality of the nodes. For example in Bellman-Ford algorithm, each node broadcasts the cost of paths to destination to all its neighbors. Based on these broadcasts each node decides which neighbor would be next hop for each destination. However because of the unidirectional nature of the wireless links, a node may receive routing advertisement from a node but may not be able to use the node as next hop. Reactive routing protocols like AODV and DSR also depend on existence of reverse routes in order to route the reply packets.

So transmit power effects all layers of the protocol stack. Also it renders many of the standard protocols belonging to the OSI stack ineffective. Thus there is a definite need for cross layer design of the transmit power control protocols. In the next subsection we briefly present the design principle for power control as stated in [6]. These principles guide the placement of power control functionality in the network protocol stack.

B. Design principles for transmit power control protocols

We enumerate various principles that guide the design of transmit energy control algorithm

- *Effect of power control on capacity*: As the transmit power of the nodes decrease the capacity of the network increases. If a node transmits a packet using power P, then the average number of nodes it interferes with is approximately $\lambda(\frac{P}{\beta})^{2/\alpha}$, where λ is the node density, β is the receive threshold of the nodes, and α is the propagation constant of the medium. So as P decreases the number of nodes with a node interferes with decreases which enhances spatially reuse. This means that as P decreases a larger number of nodes are able to transmit concurrently. However if the transmit power decreases below a certain threshold then the network becomes disconnected. So in order to optimize the capacity each node must transmit at the lowest possible power while ensuring that the network is connected.
- *Effect of hardware on power control*: Table V-B shows the various components of power consumption in a wireless card. If $P_{Tx_{Rad}}$ dominates the power consumption (which is normally the case), then an efficient way to conserve energy is to implement energy efficient routing algorithms. The energy efficient routing algorithms ensure that the traffic is routed through a path that minimizes the energy consumed due to the transmissions. When P_{Sleep} is much less than P_{idle} then a possible way to save energy is to turn off the radio whenever the node is not scheduled to transmit or receive. When a common power level is used throughout the network then there exists a critical transmission range, denoted by r_{crit}, (and corresponding transmit power), below which the transmission are suboptimal with regards to power consumption [6]. The critical transmission range is given by
$$r_{\text{crit}} = \left(\frac{P_{Rx_{elec}} + P_{Tx_{elec}}}{c(\alpha - 1)}\right)^{1/\alpha} \qquad (2)$$
However a larger transmission range may be required in order ensure the connectivity of the network
- *Effect of load on power control*: The end to end delay is sum of propagation, processing and queuing delays. The propagation delay is proportional to the distance between the source and the destination and is generally negligible. The processing delay – the time taken to receive, decode and retransmit the packet – is proportional to the number of hops between the source and destination. Queuing delay – the time spent by the packet waiting in a queue to be transmitted because the channel is busy – depends on the accessibility of the medium. When the load in the network is low then queuing delay is quite small since the number of nodes contending for the channel is very small. So in low load conditions the processing delay dominates the end-to-end delay. So the performance of a network with low load may be increased by increasing the transmit power. On the other hand if the network

is highly loaded then the queuing delay is the dominant part of the delay. The queuing delay may be decreased by reducing the contention for channel by decreasing the transmit power. Therefore the nodes must decrease the transmit power when the network is highly loaded. So the transmit energy of the nodes should vary inversely with the load on the network.

- *Power control as a network layer problem*: In [6], the authors proclaim that the transmit power control is a network layer problem. The transmit control problem had previously been solved using MAC-physical layer approaches. These strategies simply transmit the packet with smallest possible power so that the SINR at the receiver is just above the receive threshold. However intended receiver of the transmission are determined by the network layer through its routing tables. The job of the lower levels (MAC and physical layers) is to simply transmit the packet to the receiver specified by the higher layers. Thus placing the power control functionality at MAC layer does not give routing layer the opportunity of choosing the optimal next hop. In other words, the MAC approach to transmit power control problem leads to local optimization while the placing the power control functionality at the network layer leads to global optimization.

C. Some transmit power control protocols

In the previous subsection we presented some design principles of transmit power control and observed that power control must be implemented as a network layer protocol. In this section we present some power control protocols that have implemented at the network layer [6].

1) *COMPOW*: The COMPOW power control protocol is the simplest power control protocol at the network layer. In COMPOW each nodes chooses a common power level. The power level is chosen such that the network remains connected. This can be achieved by running multiple independent routing protocols, one for each feasible power level, and a COMPOW agent figures out the lowest possible power level that ensures connectivity of the network. The protocol has nice features like bidirectional links which allows all OSI protocols to operate normally over network. This protocol provides good performance when the nodes are uniformly spread in the networks. The performance of COMPOW would be highly degraded in presence of few isolated nodes that require large transmission power for ensuring connectivity. This problem is avoided in the CLUSTERPOW power control protocol.
2) *CLUSTERPOW*: In CLUSTERPOW power control protocol each node runs a routing protocol at each feasible power level p_i and thus maintains a routing table RT_{p_i} for each power layer. In order to route a packet to destination d, a node looks up the routing tables for d in increasing order of the corresponding power level. So the network layer makes sure that the packet is transmitted with lowest possible power at each hop. The CLUSTERPOW requires multiple routing daemons, one corresponding to each power level, and a CLUSTERPOW agent to coordinate the lookup of the multiple routing tables. Not only does CLUSTERPOW provides efficient power control it also provides a distributed clustering mechanism based on the transmit power. Also CLUSTERPOW can be used with any routing protocol and is proven to be loop free in [6].
3) *MINPOW*: The COMPOW and CLUSTERPOW protocols try to optimize capacity by increasing spatial reuse. MINPOW routing protocol globally minimizes the power consumption in the network. MINPOW employs distributed Bellman Ford algorithm in order to find minimum energy paths between source and destination. The link cost is set equal to the sum of $P_{Tx_{elec}}$, $P_{Rx_{elec}}$ and $P_{Tx_{Rad}}(p_l)$, where p_l is the minimum power level required in order to transmit packet across link l. $P_{Tx_{elec}}$ and $P_{Rx_{elec}}$ are known but p_l has to be estimated for knowing $P_{Tx_{Rad}}(p_l)$. Estimation of p_l cannot be accurately done based on the distance of nodes and the propagation model since both estimate of distance between node and the link model have high errors. So MINPOW estimates p_l using control packets at the network layer.

It has been shown through simulation that the energy control protocols discussed in this section outperform the existing routing protocols like DSDV in various kinds of topologies.

VI. Conclusion

In this case study we studied the problem of protocol design for wireless ad hoc networks. More precisely, we discussed many positive and negative aspects of the cross layer design approach. Although the cross layer design may provide performance optimization, it leads to a increased cost of deployment, endangers stability and would hinder the proliferation and development of wireless networks. So aggressive use of cross-layer design is not a good idea. A better approach would be to carefully assess the placement of various functionalities within the protocol stack and minimize its dependency on the information from other layers. The approach is illustrated by the example of design of transmit power control protocols for wireless ad hoc networks.

It should however be noted that cross layer design may be a suitable approach for stand alone wireless networks that are dedicated to a single application, specially if the task is highly critical, e.g. surveillance of a nuclear plant, gathering of seismic information for predicting earthquakes, data gathering behind enemy lines etc. In such networks reliability and performance are more important than cost. Also since a single application has to be supported we don't have to worry about issues like inter-operateability. Thus aggressive use of cross layer design could be highly valuable for such task oriented networks.

REFERENCES

[1] E. Ayanoglu, S. Paul, T. F. LaPorta, K. K. Sabnani, and R. D. Gitlin. Airmail: a link-layer protocol for wireless networks. *Wireless Networks*, 1(1):47–60, 1995.

[2] J.-M. Choi, J. So, and Y.-B. Ko. Numerical analysis of IEEE 802.11 broadcast scheme in multihop wireless ad hoc networks. In *ICOIN*, pages 1–10, 2005.

[3] S. Floyd. Tcp and explicit congestion notification. *SIGCOMM Computer Communication Review*, 24(5):8–23, 1994.

[4] A. J. Goldsmith and S. B. Wicker. Design challenges for energy-constrainted ad hoc wireless networks. *IEEE Wireless Communications*, 9(4):8–27, Aug. 2002.

[5] V. Kawadia and P. R. Kumar. A cautionary perspective on cross-layer design. *IEEE Wireless Communications*, 12(1):3–11, Feb. 2005.

[6] V. Kawadia and P. R. Kumar. Principles and protocols for power control in wireless ad hoc networks. *IEEE Journal on Selected Areas in Communications*, 23(1):76–88, Jan. 2005.

[7] M. Madueno and J. Vidal. Joint physical-MAC layer design of the broadcast protocol in ad hoc networks. *IEEE Journal on Selected Areas in Communications*, 23(1):65–75, Jan. 2005.

[8] P. P. Pham, S. Perreau, and A. Jayasuriya. New cross-layer design approach to ad hoc networks under rayleigh fading. *IEEE Journal on Selected Areas in Communications*, 23(1):28–39, Jan. 2005.

[9] Y. Wu, P. A. Chou, Q. Zhang, K. Jain, W. Zhu, and S.-Y. Kung. Network planning in wireless ad hoc networks: a cross-layer approach. *IEEE Journal on Selected Areas in Communications*, 23(1):136–150, Jan. 2005.