Cross-Layer Design of MANETs: The Only Option

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***Abstract*— The current Internet Protocol (IP) architecture model for mobile ad hoc network (MANET) routing protocol development ignores cross-layer effects by seeking to emulate as closely as possible the wireline architecture. Nevertheless, cross-layer effects are unavoidable and it is actually desirable to exploit these interactions to achieve greater performance. Further, support for cross-layer information flow is necessary for many of the applications envisioned for MANETs. We review the purpose of the IP architecture and argue that the MANET architecture model is not only unsuitable for exploiting cross-layer effects it also violates the very intent of the IP architecture. By focusing the standardization effort on making routing solutions and placing them at the point of integration, just above IP in the protocol stack, it effectively stifles the IP development goals of supporting local subnetwork optimization and long term innovation. We review issues of cross-layer design and then propose an alternative standardization effort that would preserve the opportunity for innovation while ensuring the integration of MANET subnetworks into larger integrated heterogeneous IP networks. Our proposal places MANET into its own subnetworking layer and then divides standardization into four parts: the interface to the MANET subnetwork, a heterogeneous routing protocol, mechanisms for cross-layer information flow, and a combined logical and spatially hierarchical addressing scheme. We identify several more radical MANET design proposals that depart substantially from the current model. All could be integrated into a larger heterogeneous IP network using our protocol approach.**

***Index Terms*—Cross-layer design, heterogeneous networks, Internet Protocol, IP, mobile ad hoc network, MANET, layering, modularity, protocol layers, standards, system design**

I. Introduction

THE most common argument justifying the use of mobile ad hoc networks (MANET) is to provide a networking solution in an environment where there is no infrastructure, yet ironically, much of the research in MANETs and the attendant standardization efforts proceed as though the ultimate purpose of MANETs is to provide "last mile" connectivity to infrastructure networks. This is no where more evident than in current standardization efforts that are directed at building ad hoc networking solutions in the internet protocol stack. Although these efforts are well intentioned we contend that they may be doing more harm than good by both preventing the very applications that these networks are intended to support and by disabling or at least complicating a significant portion of the design space that should be exploited to achieve performance. This paper attempts to clarify this viewpoint and then provides an alternative standardization approach that would be more open to the applications we believe are the objective and the innovation which will deliver the performance needed.

The critical shortcoming of the current standardization approach is that it is trying to fit a wireless problem to a static wireline paradigm. The necessary abstractions that occur between the layers of this design cannot remove the interactions that occur between the layers and prevents some of the desired interactions that can be exploited to achieve better performance. Cross-layer effects are unavoidable and occur between all layers even the application and the physical (e.g. the movement of users can disable connections and partition the network.) In this paper we propose an alternative standardization approach that embraces cross-layer interactions and enables their exploitation while trying to retain the ability to integrate ad hoc networks with their wireline cousins through the Internet Protocol (IP).

Our presentation begins with a simple example of how the applications of MANETs used in tactical environments differ from those of infrastructure environments. We follow with a discussion of the unique features of ad hoc networks. These two introductory sections reveal the rich set of cross-layer communications that should occur among the traditional network layers. In the fourth section we review the role of layering and standardization in system design. Layering enables the subdivision of system design and standardization enables integration of heterogeneous systems. We use this discussion to explain why the current standardization efforts are inadequate. We review what constitutes cross layer design and various implementation issues. Next we describe our standardization proposal. The goal of our proposal is to allow the innovation necessary for achieving performance while retaining the ability to integrate ad hoc networks with other networking technologies. We then review several new MANET networking ideas that are not practical in the current standardization approach but possible with our proposal.

II. Applications

Unfortunately, the predominant understanding of how applications might be built in ad hoc networks is driven by the ubiquitous experience that users and developers have with the Internet, their business LANs, and cellular telephony. Web-

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based services and address based communications dominate. We do not deny that these traditional applications are useful but contend that tactical applications include a completely different set of needs. To clarify this claim we provide a simple scenario. Say you are aware of a person in a distant building that is in danger and you cannot contact him verbally or visually but want to warn him. Does your both having a telephone and computer connected to the Internet help? Currently, the answer is no if you do not know his phone number or e-mail address. Tactical users need to be able to close these types of ad hoc communications regardless of their having a prior knowledge of the personal address of the distant end and must do so rapidly. The critical translation that applications must assist is each user's correlation of peers in their areas of operations to their ability to communicate to them using the network. Enabling such a capability requires users to receive feedback about their network and how their activity affects their communications capability. An analog of this type of feedback is the bar display on cellular phones that enable their users to assess whether they are in range of a base station and to take corrective action if they are not. However, in MANETs the feedback would not be so simple. The likely feedback would be a display of the network overlaid onto the situation awareness picture. Implementing this capability would require cross-layer information flow between the lower layers of the protocol stack and the application. The critical application of ad hoc networking in tactical environments is networking itself. Cross-layer design is required.

III. Unique Features of Ad Hoc Networks

A. The Media

The media in ad hoc networks is RF spectrum in space. It is not a shared link as in an Ethernet LAN or dedicated link that may be placed between two routers. The space that is used is unique to the transmitter receiver (TR) pairs but sufficient portions overlap with that of other TR pairs thus precluding the latter from using the media simultaneously. This interdependence between TR pair connectivity means there is no connected graph in ad hoc networks.

B. Limited Capacity

The RF spectrum that will be available for any MANET implementation will be finite and limited. It is not expandable like wireline capacity. Thus, the use of the capacity it renders must be efficient. It is anticipated that the demand for the capacity in MANETs will frequently reach saturation. Redundant exchange of common information by multiple layers should be avoided.

C. Radios Provide a Service

Radios and there protocols generate information that is useful to applications. The more used capabilities are generating system synchronization and terminal positioning. The two functions are complementary and are very important in many military systems and are a core function of LINK 16 and the EPLRS radios and the applications that use them. If similar radios are combined with an IP protocol stack, then provisions would be needed to send this information from the radio to the application

Further, some services in MANETs can only be implemented in access protocols. The most important are prioritized and reserved access for the quality of service. Over provisioning techniques that are used elsewhere in the internet are not practical since capacity is insufficient in most MANET implementations. A discussion of access mechanisms for QoS can be found in [1]. To access these services, applications need a way to communicate the QoS requirements through the protocol stack to the MAC.

D. Similar Information Useful to Different Layers

The most obvious piece of information that is useful at multiple layers is the location of terminals. We have already seen that there is a real need for applications to have location information and that it can even be generated by the radio terminals. Location information can also support antenna pointing, transmission scheduling, routing, network management, and spectrum management.

Congestion information at nodes and in spatial regions is useful for access protocols, routing, transport control, call admission and network management.

Node mobility is useful to applications, routing, antenna pointing, and scheduling.

The energy status of nodes is useful to routers so paths can be chosen to avoid energy deficient nodes and to access protocols so that they can choose appropriate dozing strategies.

Transmission schedules created by access protocols are useful to routing protocols so they know how resources have been allocated and can route through regions that are adequately provisioned.

E. Distributed Information Exchange

In addition to sharing information, many protocols of all types have a need to distribute information to support their operation. Routing protocols are obvious. Access protocols that use multiple channels need mechanisms to disseminate the use of channels. Access protocols may also require the dissemination of access schedules. Network and spectrum management protocols are useful to MANETs and require information distribution to function. Within the homogenous environment of a MANET, it is feasible to combine this distribution within a single protocol, see [1]. Since multiple layers require common information, it is also more efficient.

F. Cross-Layer Decisions

Many proposed MANET implementations benefit from cross-layer decisions, especially between transport control, routing, and access protocols. Consider TDMA access mechanisms. Reservations are made at the access protocol to support flows. They can either be created in response to demand and the routes that are calculated to best support the flow or vice versa they can be created and routes can be chosen based on what is available. This sort of interaction is also appropriate for other ways of managing the shared media using different channels in the frequency dimension or antenna technology in the spatial dimension.

MANETs are prone to partitions. Disruption tolerant networking (DTN) proposes a store and forward technique where proxies at the partition edges can store communications until the partitions are closed. The choice of the proxy is made based on knowledge of the networks current and anticipated connectivity, information that is generated by the routing protocols [2].

G. *Unavoidable Cross-Layer Interactions*

Above, we have identified a number of reasons cross-layer design may be beneficial to MANETs. Here we make the point that cross-layer interactions are unavoidable. Unfortunately, in wireless networks the quality of links can vary dramatically [3]. Consider a routing protocol that uses a minimum hop metric, i.e. all links are equal. The minimum hop metric will generally choose links at the threshold of connectivity (i.e. the longest links) and so where signals are weakest and fading effects have the greatest consequence. These links are the most likely to come and go causing the routing protocol to continuously update. This was found to be very debilitating, even for a small number of nodes, <10, when a well know MANET routing protocol of this type was used in a harsh RF environment with 802.11b modems [4]. The problem was solved by creating a metric for the link quality.

Minimum hop routing algorithms can also counter the effects of lower layer optimizations. Say the modem is designed to be rate adaptive, i.e. uses higher transmission rates when the signals are strong. Since the minimum hop metric encourages weak links there would be less opportunity for the rate adaptation to have an effect.[1] Routing protocols need to be designed with an appreciation of what is happening at the physical layer.

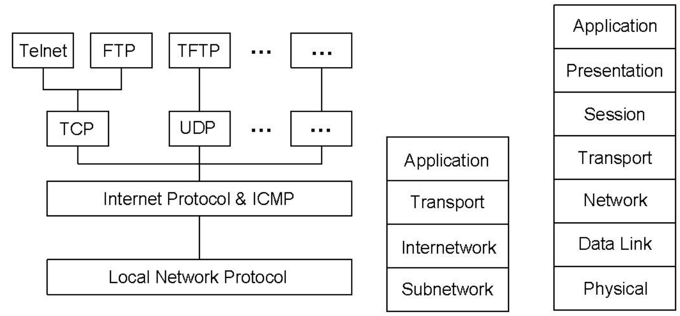
IV. Network Layering Models

A. *The Role of Layering*

The purpose of layering or blocking in any system design is to create modularity. Each module has a defined function that contributes to the overall system function. Modularity allows experts in the different domains of an overall system to concentrate on the details of the design of the modules in their domain while abstracting adjacent modules to their functions and services and the required communications that should occur between them.

B. *Models*

Multiple models of networking exist. Two stand out, the original Internet Protocol (IP) model [5] and the Open Systems Interconnection – Basic Reference Model [6]. There is not really an official IP model but from the illustrations within the specification and the discussion one is implied. Our Fig. 1a



a. Figure 1 of RFC 791 showing protocol relationships b. Implied IP layered model c. OSI layered model

Fig. 1. Network models showing layer and protocol relationships

replicates the first figure in the specification and Fig. 1b illustrates the protocol layers it implies. Figure 1c illustrates the OSI model. We see two distinctive differences. Above the network layer, the OSI model has two layers, presentation and session, that are not in the IP model. This distinction is not an issue in this discussion. The second distinction is the description of what lies beneath the network layer. The IP model only shows a subnetwork while the OSI model shows a data link and a physical layer. This distinction is very germane. The OSI model implies that the network connects a set of links whereas the IP model shows the internetwork connecting a set of subnetworks. This difference is at the kernel of our argument on how standardization should proceed to better support MANET implementation and integration into larger IP networks.

C. *The Role of Layer Standardization*

The first role of standardization is to define the interfaces and performance tolerances of the layers. This allows many different types of modules to be defined that can all be inserted into a system. Further, new systems can be developed using layers already defined for use in other systems so long as the functions are appropriate and the new system adheres to the interfacing requirements.

A distinction of networking systems is that that they are distributed. Layers instantiated by a node not only interact with the adjacent layers at that node but also interact with the same layers instantiated by other nodes. This puts a greater demand on the level of standardization. The specific details of the layer are standardized or else they will not interoperate. For example, a Carrier Sense Multiple Access (CSMA) medium access control (MAC) protocol would not interoperate with a Time Division Multiple Access (TDMA) MAC although either could interact with the adjacent layers of either node. Since different vendors may build components these standards are the hardest to agree to and are the most critical for product commercialization. The 802.11 standards are examples.

D. *Balancing Innovation, Integration, and Commercialization*

A limitation of standards is that they can easily restrict innovation. So in system design, it is conventional wisdom to make standards minimally prescriptive leaving opportunity for

[1] This is an example from [14] to support the argument that cross-layer issues must always be considered in ad hoc networks.

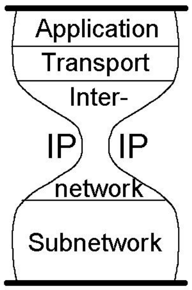


Fig. 2. The Internet Protocol hourglass

present and future developers of modules to innovate. In a non-distributed system, standards of the first type that define interfaces and functions are appropriate. The issue is how to deal with distributed systems. Detailed standards will apply but only to support the production of common functionality by different vendors, otherwise interoperability can be achieved by making copies. This was the state of affairs when the internet protocol was pursued. There were already many proprietary networking solutions. The new solution that was sought was a way to get them to interoperate. Vint Cerf defined the following objective for the project in [7] stating:

"The basic objective of this project is to establish a model and a set of rules which will allow data networks of widely varying internal operation to be interconnected, permitting users to access remote resources and to permit intercomputer communication across the connected networks.

"One motivation for this objective is to permit the internal technology of a data network to be optimized for local operation but also permit these locally optimized nets to be readily interconnected to an organized catenet.[2] …

"A second motivation is to allow new networking technology to be introduced into the existing catenet while remaining functionally compatible with existing systems. This allows for the phased introduction of new and obsolescence of old networks without requiring a global simultaneous change."

The objectives were to integrate existing networking technologies, create the opportunity to optimize locally and to allow further innovation in the internet. The resulting product was a brilliant demonstration of designing a heterogeneous system of systems and the attendant role of standardization. In these systems, if the issue is performance one avoids standardization in order to leave room for innovation but if the issue is integration then standardization is the path. The developers of the internet created an internetworking protocol as the point of integration in the protocol stack and so this is the standardized module that is ubiquitous in the Internet. Fig. 2 is an illustration that is frequently used to teach this point. The protocol hourglass shows the internet protocol at the neck indicating that all traffic through the layers must convert to IP. But the second message is that the width of the hourglass reveals the opportunity to innovate. IP is the point where standardization occurs so innovation is limited there but this frees up the remaining layers for innovation.

[2] The term "catenet" was defined as "the collection of packet networks which are connected together."

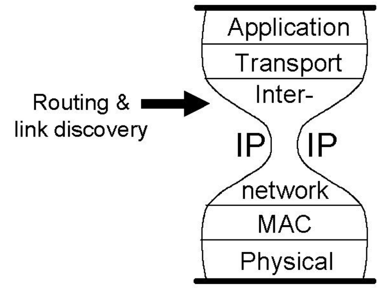


Fig. 3. Modified Internet Protocol hourglass for the MANET standardization effort

From our discussion we see there are two drivers to creating detailed standards, promoting integration of systems and promoting commercialization of components. Standardization of components that are replaceable in the network does not restrict innovation but if those standards reside at the point of integration, the Internetworking layer, then they will, and that is the state of affairs today.

E. Current Standardization Activities that Affect Ad Hoc Networking

There are two MANET standardization efforts under the auspices of the Internet Engineering Task Force (IETF), the MANET working group (WG) and the MANET-OSPF work in the OSPF WG. Both are trying to solve routing at the IP layer. The rationale presented in [8] reveals that the intent of the MANET WG was to make different wireless technologies interoperable. What was not specified was whether the wireless technology was to be a subnetwork or something else. We redraw Fig 2 in Fig 3 to illustrate what has resulted. We find that the standardization effort has proceeded with the view that the wireless modem is merely a MAC protocol and its physical layer, e.g. an 802.11 modem. The routing protocols perform link and topology discovery and routing table calculation. Now consider our discussion of the natural cross-layer communications that are appropriate in ad hoc networks and the competing objectives of integration and innovation in heterogeneous systems. The MANET WG is viewing routing as an integration problem and their standardization effort is limiting the scope of what the wireless technology should do. In effect it has removed a substantial portion of the design space necessary for innovation. Local optimization is thwarted as this is achieved by adjusting parameters in the protocol implemented at the point of integration. More importantly, the mindset that routing in a MANET should occur at the IP layer will perpetuate this predicament since protocol implementations at IP should support the integration of different technologies and these solutions are designed for a single type of technology.

V. Cross-Layer Designs

Cross-layer design is broadly defined as "actively exploiting the dependence between protocol layers to obtain performance gains [9]." Here we review the key models for cross-layer designs and discuss the implementation issues.

A. Cross-layer models

Six different types of cross-layer design proposals are identified in [9]. Three are based on information flow that occurs across one or more layers, upward, downward, and back-and-forth. Designs where higher layer protocols need information about lower layers are upward flow designs. Lower layer protocols that receive direction from higher layer protocols are downward flow designs. Pairs of protocols at different layers that collaborate in networking solutions are back-and-forth designs. The fourth cross-layer design approach is to consolidate the functionality of multiple layers into a single optimized layer. The last two designs are more performance optimization approaches where efforts to improve the performance of a layer are executed in other layers without direct communications. There are two types, design coupling and vertical calibration. In design coupling, layers are coupled at design time without any extra interfaces. Usually an upper layer is designed with specific knowledge of the lower layer's capabilities. MAC and physical layer design is the more obvious example since most MAC protocols at the very least must consider how fast the physical layer processes RF signals and transitions between transmitting and receiving states. Vertical calibration seeks network performance by tuning all protocol layers.

Of the cross-layer models, coupled designs and vertically calibrated designs, specifically those that involve protocols above IP, are the most problematic for integrating MANETs into IP networks. Those layers that are coupled to achieve MANET performance may be counterproductive in the wireline network. In addition, changes in any one of the coupled layers may require attendant changes in the other coupled layers thus defeating the whole purpose of modularity.

B. Cross-layer implementation

Protocol implementation must balance ease and cost of development with performance. Placement of functionality can be in the user space, the kernel, or in the firmware of the modem, with the ease of development and customization decreasing in that order. Referring to Fig. 3, we find that the MAC and the physical layer are part of the modem, that IP is part of the operating system kernel, and that MANET development of link discovery and routing occurs in the user space, frequently using the services of the User Datagram Protocol (UDP) of the transport layer. Ease of development and more importantly, just the accessibility to the development space are clearly motivations.

Meanwhile, performance, and here we mean performance as the speed at which protocols can process packets, make decisions, and react to conditions, is very sensitive to where and how protocols are implemented. The feasible set of actions that can be taken by protocols will depend on this location. In MANETs, a substantial number of the cross-layer types of decisions attempt to control the physical layer. Execution of decisions made in protocols implemented in the user space will be relatively slow as compared to the execution of decisions made in the device. Protocols that control the physical characteristics of a transmission where adjustment occurs on a per packet basis may not be effective if implemented in the user space. The user space is inappropriate for deciding adaptations that result from observations that occur in handshake packets or that occur just prior to contention and transmission.

In implementation, retaining protocol modularity may not be a good thing. Interfaces, because they are fixed, lead to uncertainty as to what one layer expects from another [10]. For example, if a routing protocol uses received signal strength measurements to ascertain the quality of a link it would need that information to be communicated from the physical layer. Say a modem can provide this information and a routing protocol can use it. Because of modularity, neither should assume the other. The modem cannot assume that the routing protocol needs or can process the information unless all routing protocols can use it nor can the routing protocol assume that the modem can provide the information. It is precisely because of this ambiguity that there is design coupling where higher and lower layer protocols are designed concurrently to exploit the unique capabilities of the other. Designs of this type are made modular for the sake of being modular. They do not achieve the goal of allowing the interchange of modules. The current work to create modular routing protocols that provide a modular view are problematic as well. Recall our discussion about the unavoidable interactions that can occur with minimum hop routing protocols, they can choose the worst links for routing and they can work counter to the very intent of MAC-physical layer optimization efforts.

Thus there is a dilemma in MANET protocol implementation. Development and implementation of MANET solutions is easiest in the user space but this precludes using routing protocols that exploit the physical layer unless they are designed for specific modems, which in turn violates the whole purpose of standard modules. Additionally, implementations that are totally modular may preclude some intuitively appropriate modem optimizations. The presence of IP between the routing module and the modem will always make this so.

VI. A Standardization Proposal

Our goal is to integrate MANETs into an IP protocol stack while being true to the original internet work by leaving room for local optimization and continuous innovation. This goal is clearly prevented by the approach of standardizing methods of discovering MANET topology and routing at IP. We believe the best approach is to return to the original concept of internetworking where IP is meant to integrate a set of different subnet technologies. MANETs themselves should be considered subnets where solutions are created for a homogenous stack of routing, MAC, and physical layers. Implementing this type of solution requires several questions be answered. How does the very dynamic membership and connectivity of the MANET get conveyed to whatever routing protocol is implemented and how should the routing protocol that is used at IP integrate different subnetworking technologies? Additionally, how can we expand TCP/IP to allow the rich set of cross-layer

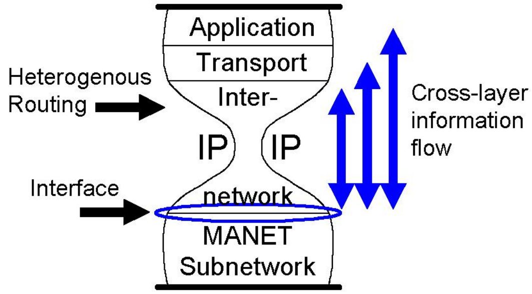


Fig. 4. Internet Protocol hourglass for our proposed MANET standardization effort

communications that are not only beneficial but necessary for many of the intended applications? Finally, a problem we have not yet defined is how do we handle addressing? Answering these questions should be the role of standardization.

Fig. 4 illustrates the hourglass model of our proposal. There are four parts of the problem, an interface between the internetwork and the MANET subnetwork, a routing protocol that is intended to support routing across subnets, methods for information flow across the layers, and finally, not illustrated, is an addressing approach. Greater details follow.

A. *Interface*

Interface standardization should define the minimum set of communications that can occur and the methods used to specify their capabilities. We believe very strongly that the protocols above the interface should avoid loading the MANET subnetwork. Any information on subnetwork state and its performance should be collected internally by the protocols of the MANET subnetwork where collection and interpretation can be optimized for the specific technology. And so, the interface defines the minimum and optional types of information that the heterogeneous routing protocol can request and the formats for the information exchange. The minimum requirement is for the sunbnetwork to present the collective set of nodes in the subnetwork that are accessible through the interface with an appropriate metric(s) for reaching each of them. Similarly, the heterogeneous routing protocol could present more efficient border routes that are possible between nodes in the subnet routing protocol. The interface should also allow the subnetwork to specify its capabilties. Subnetworks may vary from the most simple that deliver packets in a best effort sense to those that can provide varying levels of QoS. The interface should define the management type communications that can be directed to the subnetwork. Finally, each radio should be able to learn the configuration of the node and the identification of the other subnets of the node

B. *Heterogeneous Routing*

The heterogeneous routing protocol integrates the disparate routing problems of MANET and wireline networks. This routing protocol differs from those being created by the MANET WG in that it does not attempt to discover topology. In cases where the only IP interface is to a MANET, it simply uses the connectivity information to identify whether a packet should or should not be sent. It will send packets to nodes in the subnet and if there is a default router in the subnet send all other packets to that node. Routing is done within the subnet until it gets to the destination or the default router. In cases where there are multiple interfaces to different MANET subnets we expect these to form a hierarchy based first on scope and then radio range. Table 1 lists a hierarchy that is illustrated in Fig. 5. Most entities have more than one radio, each belonging in different subnets. If the destination is not in a nodes local view of any of its subnets, the packet is routed to the nearest node in the next highest hierarchy. To support this capability, routing protocols would need to track the configuration of individual nodes and their network membership. Here is where heterogeneous networking is also more interesting. The protocol would need mechanisms to share subnet views and rules about how views are shared. Finally, the heterogeneous networking protocol would need to accommodate standard wireline technologies. Rather than obtain the topology from the subnet, here the protocol would need to provide a route discovery mechanism.

TABLE 1. MANET SUBNETWORK TYPES

Level	Platforms	Scope	Radio Range	Purpose
0	airborne, vehicle	global	50+ km	MANET*
1	vehicle	global	10-20 km	MANET*
2	vehicle, handheld	global	3-5 km	MANET*
3	vehicle	local	10-20 km	C2 Voice**
4	vehicle, handheld	local	3-5 km	C2 Voice**

* MANET created with the intent that all radios can communicate to each other but does not imply that the MANET can route between all radios.
** C2 Voice radios form a small subnet with restricted membership such as a platoon, company, or battalion voice network. The objective is to pull high volume multicast traffic that supports a small subset of users onto a separate channel.

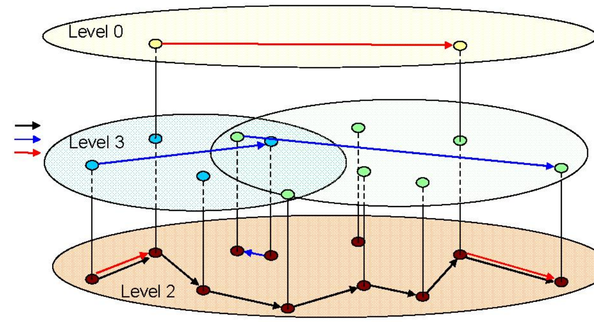


Fig. 5. Routing through spatially hierarchical subnetworks

C. *Cross-Layer Information Flow*

Even with the consolidation of MANET subnetworking technologies beneath IP there is still a need for cross-layer communications. We have already seen that the heterogeneous routing protocol needs to share information with the subnet. But the more radical types of cross-layer communications are those described at the beginning of the paper where applications access information generated by the MANET and its radios. Proposed approaches to cross-layer signaling include putting information in packet headers, using the Internet Control Message Protocol, creating local databases of information for all layers to access, or allowing direct signaling among the layers [11]. Most of these techniques do not offer the flexibility we envision as necessary or are not generic enough to be standardized and be true to our design objectives. A possible approach is to use IP packets themselves but allow them to address the layers. A set of loopback addresses could be chosen to target specific layers. The combination of interface and loopback addresses can be used to reach through IP to the protocols operating in the modems that interface to the subnetworks.

D. Addressing

Addressing presents a very significant challenge. Logically hierarchical addressing is the foundation of scalable routing in the internet. However, logical hierarchy does not work in MANETs as their volatility prevents such a hierarchy from even being created. In cases where it is used it is forced on the network a priori and results in less operational flexibility. But what is very apparent about MANETs is that spatial context is significant and that spatial hierarchy could possibly support the addressing problem. The large address space of IPv6 may provide opportunities to create address structures that can support the duality of a logical and spatially hierarchical addressing structure.

VII. Current Innovative work

The lack of progress in MANET solutions has led to several efforts to try to reinvent the ad hoc networking problem. The current DARPA program Core Based MANET, is attempting a "*tabula rosa* rethinking" of the network stack. The apparent goal is to create a stack appropriate for ad hoc networking that also exploits cross-layer design [12]. New signal processing techniques that allow concurrent reception of multiple packets can lead to radical redesign of the MANET architecture which is proposed in [13]. Rather than a single link-by-link propagation of packets through the networks the author envisions a co-operative transport where multiple nodes transmit the same packets to create multiple parallel paths with the objective of greater end-to-end reliability. Unique to these transmissions is that intermediate nodes operate in a full-duplex mode where they start retransmitting the packets as they receive them. Whole paths are instantiated for flows between distant source destination pairs. A third rethinking is one that we have proposed where access and routing is executed entirely from a spatial sense [1]. Access protocols arbitrate access by arbitrating spatial separation of contenders. The routing protocol tracks node states and infers the existence of links with these states. There is no explicit dissemination of link observations.

All of these approaches can be pursued without regard for IP networks but assuming there is still a need to integrate the MANET solutions with IP networks, the approach proposed in this paper could be used.

VIII. Conclusion

In this paper we first argued that cross-layer design is inherently necessary for MANETs and their applications. We then argue that current standardization efforts are creating networking solutions that not only do not take this into account but also prevent some very necessary cross-layer interactions, cause others that are undesirable and, further, even miss the objective of IP standardization stifling both local optimization and innovation. We then provide an alternative standardization approach that attempts to isolate MANET development as a subnetworking technology so local optimization and innovation are possible. We identify four parts to the standardization problem, an interface between the MANET subnetwork and an integrated heterogeneous internetwork, a routing protocol for this type of heterogeneous internetwork, a method for cross-layer signaling in the protocol stack, and finally a reconsideration of addressing structure to support both logical and spatial hierarchies in the network. We conclude with some ideas and research efforts that are cutting edge in their innovation but clearly non-conformal to the current standardization effort. All would be supported by our standardization proposal. Moving forward with this type of standardization effort may unleash the innovation that can let MANETs live up to expectations.

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