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Mobile Ad Hoc Network

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Abstract

Mobile Ad Hoc Networking is an emerging technology that supports self-organizing, mobile networking infrastructures, and is one which appears well-suited for use in future commercial and military applications. This article presents an overview of Mobile Ad Hoc Networking technology and current Internet Engineering Task Force standardization efforts in this regard. It gives long-term rationale for following an Internet Protocol-based networking approach in these mobile wireless systems. It also discusses some current limitations of the technology and gives several areas for future work.

1 INTRODUCTION

A **mobile ad hoc network** (**MANET**), is a self-configuring infra structureless network of mobile devices connected by wireless links. *ad hoc* is Latin and means "for this purpose". [1] [2]

Each device in a MANET is free to move independently in any direction, and will therefore change its links to other devices frequently. Each must forward traffic unrelated to its own use, and therefore be a router. The primary challenge in building a MANET is equipping each device to continuously maintain the information required to properly route traffic. Such networks may operate by themselves or may be connected to the larger Internet.

MANETs are a kind of wireless ad hoc networks that usually has a routeable networking environment on top of a Link Layer ad hoc network.

The growth of laptops and 802.11/Wi-Fi wireless networking have made MANETs a popular research topic since the mid 1990s. Many academic papers evaluate protocols and their abilities, assuming varying degrees of mobility within a bounded space, usually with all nodes within a few hops of each other. Different protocols are then evaluated based on measure such as the packet drop rate, the overhead introduced by the routing protocol, end-to-end packet delays, network throughput etc.

Mobile Ad Hoc Networking technology, also known as Mobile Packet Radio, has been under sporadic development for over 20 years, primarily through research funded by the U.S.Government. Today, government-sponsored work is still underway in networking programs such as the Tactical Internet and Near-Term Digital Radio [NTDR], DARPA's Global Mobile[GloMo] and Small Unit Operations [SUO] Programs, and the Army Research Laboratory's Advanced Telecommunications and Information Distribution Federated Laboratory Program [ATIRP]. The technology enables networked operation of an autonomous system of mobile nodes, and has long been seen as being well-suited for enabling peer-to-peer operation in forwarddeployed military networks. More recently, commercial radio technologies have begun to appear which also provide opportunities for commercial applications of the technology, as is evidenced by commercial standards efforts such as the ETSI HIPERLAN Wireless LAN (WLAN) standard [HIPERLAN],

IEEE 802.11 WLAN standard [802.11] and the recent work within the Bluetooth consortium [Bluetooth]. This article presents an overview of Mobile Ad Hoc Networking technology and current Internet Engineering Task Force (IETF) standardization efforts. In so doing, it provideslong-term justification for following an Internet Protocol (IP)- based networking approach in these mobile wireless systems. It describes architectural concepts evolving as a result of work within the IETF's Mobile Ad Hoc Networks (manet) Working Group; discusses current limitations of the technology; and raises research issues being addressed to make the technology more widely applicability for use in the future.

1. Types of Mobile ad hoc network

- **Vehicular Ad Hoc Networks (VANETs)** are used for communication among vehicles and between vehicles and roadside equipment.
- **Intelligent vehicular ad hoc networks (InVANETs)** are a kind of artificial intelligence that helps vehicles to behave in intelligent manners during vehicle-to-vehicle collisions, accidents, drunken driving etc.

1.1 Vehicular Ad Hoc Networks:

A **Vehicular Ad-Hoc Network**, or **VANET**, is a technology that uses moving cars as nodes in a network to create a mobile network. VANET turns every participating car into a wireless router or node, allowing cars approximately 100 to 300 metres of each other to connect and, in turn, create a network with a wide range. As cars fall out of the signal range and drop out of the network, other cars can join in, connecting vehicles to one another so that a mobile Internet is created. It is estimated that the first systems that will integrate this technology are police and fire vehicles to communicate with each other for safety purposes.

Applications of Vehicular Ad Hoc Networks:

Most of the concerns of interest to MANets are of interest in VANets, but the details differ. Rather than moving at random, vehicles tend to move in an organized fashion. The interactions with roadside equipment can likewise be characterized fairly accurately. And finally, most vehicles are restricted in their range of motion, for example by being constrained to follow a paved highway.

In addition, in the year 2006 the term *MANet* mostly describes an academic area of research, and the term *VANet* perhaps its most promising area of application.

VANET offers countless benefits to organizations of any size. Automobile high speed Internet access would transform the vehicle's on-board computer from a nifty gadget to an essential productivity tool, making virtually any web technology available in the car. While such a network does pose certain safety concerns (for example, one cannot safely type an email while driving), this does not limit VANET's potential as a productivity tool. It allows for "dead time"—time that is being wasted while waiting for something—to be transformed into "live time"—time that is being used to accomplish tasks. A commuter can turn a traffic jam into a productive work time by having his email downloaded and read to him by the on-board computer, or if traffic slows to a halt, read it himself. While waiting in the car to pick up a friend or relative, one can surf the Internet. Even GPS systems can benefit, as they can be integrated with traffic reports to provide the fastest route to work. Lastly, it would allow for free, VoIP services such as GoogleTalk or Skype between employees, lowering telecommunications costs.

Technology

InVANET, or Intelligent Vehicular Ad-Hoc Networking, defines an Intelligent way of using Vehicular Networking. InVANET integrates on multiple ad-hoc networking technologies such as WiFi IEEE 802.11 b/g, WiMAX IEEE 802.16, Bluetooth, IRA, ZigBee for easy, accurate, effective and simple communication between vehicles on dynamic mobility. Effective measures such as media communication between vehicles can be enabled as well methods to track the automotive vehicles is also preferred.

InVANET helps in defining safety measures in vehicles, streaming communication between vehicles, infotainment and telematics.

Vehicular Ad-hoc Networks are expected to implement variety of wireless technologies such as Dedicated Short Range Communications (DSRC) which is a type of WiFi. Other candidate wireless technologies are Cellular, Satellite, and WiMAX. Vehicular Ad-hoc Networks can be viewed as component of the Intelligent Transportation Systems (ITS).

Vehicular Networks are an envision of the Intelligent Transportation Systems (ITS). Vehicles communicate with each other via Inter-Vehicle Communication (IVC) as well as with roadside base stations via Roadside-to-Vehicle Communication (RVC). The optimal goal is that vehicular networks will contribute to safer and more efficient roads in the future by providing timely information to drivers and concerned authorities.

1.1 Intelligent vehicular ad hoc networks:

Intelligent vehicular ad hoc networks (InVANETs) use WiFi IEEE 802.11p(WAVE standard)and WiMAX IEEE 802.16 for easy and effective communication between vehicles with dynamic mobility. Effective measures such as media communication between vehicles can be enabled as well methods to track automotive vehicles. InVANET is not foreseen to replace current mobile (cellular phone) communication standards .

"Older" designs within the IEEE 802.11 scope may refer just to IEEE 802.11b/g. More recent designs refer to the latest issues of IEEE 802.11p (WAVE, draft status). Due to inherent lag times, only the latter one in the IEEE 802.11 scope is capable of coping with the typical dynamics of vehicle operation.

Automotive vehicular information can be viewed on electronic maps using the Internet or specialized software. The advantage of WiFi based navigation system function is that it can effectively locate a vehicle which is inside big campuses like universities, airports, and tunnels. InVANET can be used as part of automotive electronics, which has to identify an optimally minimal path for navigation with minimal traffic intensity. The system can also be used as a city guide to locate and identify landmarks in a new city.

Communication capabilities in vehicles are the basis of an envisioned InVANET or intelligent transportation systems (ITS). Vehicles are enabled to communicate among themselves (vehicle-to-vehicle, V2V) and via roadside access points (vehicle-to-roadside, V2R). Vehicular communication is expected to contribute to safer and more efficient roads by providing timely information to drivers, and also to make travel more convenient. The integration of V2V and V2R communication is beneficial because V2R provides better service sparse networks and long distance communication, whereas V2V enables direct communication for small to medium distances/areas and at locations where roadside access points are not available.

Providing vehicle-to-vehicle and vehicle-to-roadside communication can considerably improve traffic safety and comfort of driving and traveling. For communication in vehicular ad hoc networks, position-based routing has emerged as a promising candidate. For Internet access, Mobile IPv6 is a widely accepted solution to provide session continuity and reachability to the Internet for mobile nodes. While integrated solutions for usage of Mobile IPv6 in (non-vehicular) mobile ad hoc networks exist, a solution has been proposed that, built upon on a Mobile IPv6 proxy-based architecture, selects the optimal communication mode (direct in-vehicle, vehicle-to-vehicle, and vehicle-to-roadside communication) and provides dynamic switching between vehicle-to-vehicle and vehicle-to-roadside communication mode during a communication session in case that more than one communication mode is simultaneously available.

Currently there is ongoing research in the field of InVANETs for several scenarios. The main interest is in applications for traffic scenarios, mobile phone systems, sensor networks and future combat systems. Recent research has focused on topology related problems such as range optimization, routing mechanisms, or address systems, as well as security issues like traceability or encryption. In addition, there are very specific research interests such as the effects of directional antennas for InVANETs and minimal power consumption for sensor networks. Most of this research aims either at a general approach to wireless networks in a broad setting or focus on an extremely specific issue.

2. MANET Relationship to Existing Networks

This is in contrast with the topology of the existing Internet, where the router topology is essentially static—barring network reconfiguration or router failures. In a MANET, the routers may be *mobile* and inter-router connectivity may change frequently during normal operation. A MANET is an autonomous system of mobile nodes. It may operate either in isolation, or may be connected to the greater Internet via "gateway" routers. Essentially, a MANET is a "mobile routing infrastructure".

In contrast, the existing Internet and nearly all telecomm networks for that matter possess *quasi-fixed* infrastructures consisting of routers or switches which forward data over hardwired links. Traditionally, end user devices such as host computers or telephones attach to these networks at fixed locations. As a consequence, they are assigned an address based on their location in a fixed network addressing hierarchy and often times assume an identity equivalent to their address. This identity-location equivalence greatly simplifies routing in these systems, as a user's location does not change.

Increasingly, end devices are becoming mobile, meaning that they are capable of changing their point of attachment to the fixed infrastructure. This is the paradigm present in cellular telephony and its Internet equivalent—mobile IP. In this approach, a user's identity may or may not be equivalent to its location, depending upon whether or not the user adopts a location-dependent (temporary) or location-independent (permanent) identifier, respectively. Sometimes, users with temporary identifiers are referred to as "nomadic" whereas users with permanent identifiers are referred to as "mobile".

The distinction is that nomadic users may move, but principally carry out their network-related functions in a fixed location, whereas

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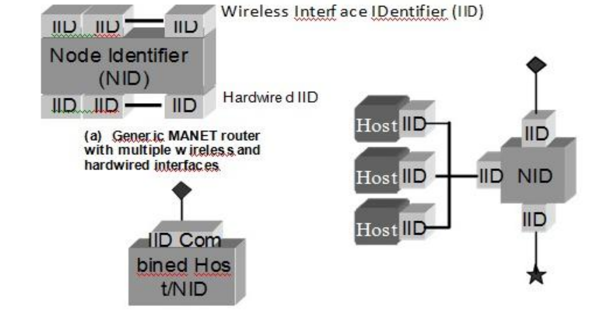
mobile users must work "on the go" changing points of attachment as necessary. In either case, additional networking upport may be required to track a user's location in the network so that information may be forwarded to its current location using the routing support within the fixed hierarchy. The situation here is such that while the end user devices may move, the networking infrastructure remains fixed. Thus, although users are mobile, much of the fixed infrastructure's networking technology can be utilized to support the mobile users.

Mobile ad hoc networking changes the game somewhat. Now, the routing infrastructure may move along with the end devices. Thus the infrastructure's routing topology may change, and the addressing within the topology may change. In this paradigm, an end user's association with a mobile router (its "point of attachment" to the MANET) determines its "location" in the MANET. As before, a user's identity may be temporary or permanent, depending on its



(c) A MANET node consisting of a host (acting as a router) with a single wireless interface

(b) A MANET node consisting of a router with two wireless interfaces and attached hosts (wired or wireless)

need.

- **Dynamic topologies**. Nodes are free to move arbitrarily. The network topology, which is typically multihop, may change randomly and rapidly at unpredictable times. Adjustment of transmission and reception parameters such as power may also impact the topology.
- **Bandwidth-constrained, variable capacity, asymmetric links**. Wireless links will continue to have significantly *lower* capacity than their hardwired counterparts. One effect of the relatively low to moderate link capacities is that *congestion* is typically the norm rather than the exception (i.e. it is likely that aggregate application demand will frequently approach or exceed network capacity). Another effect is that MANETs will have to operate in heterogeneous environments with varying bandwidth-delay characteristics.
- **Energy-constrained operation**. Some or all of the nodes in a MANET may rely on batteries for their energy. For these nodes, power conservation is a critical design criterion.
- **Wireless vulnerabilities and limited physical security.**

2.1 MANET Environment

MANETs are being designed to operate in widely varying environments. Forward-deployed military MANETs are envisioned to be relatively large, dynamic and heterogeneous, with hundreds of nodes per mobile domain. Other MANETs may be smaller in scope, essentially serving as multihop extensions of WLAN technologies. This latter usage mode is expected to have significant commercial applicability as well. On a smaller scale, low power sensor networks and other embedded systems also look to be promising application areas for MANET technology.

Across this wide range of application scenarios, MANETs have several salient characteristics that differentiate them from fixed multihop networks:

3 ADVANTAGES OF IP LAYER ROUTING

We now give rationale for using IP-based networking technology in these mobile wireless systems.

3.1 Traditional Design Approach

Traditionally, mobile packet radio systems have been "stovepipe" systems using proprietary, highly vertically- integrated technology at all levels of network control. This was due, in part, to the need to extract maximum performance from relatively low capacity, yet high-cost system components. Such networks were typically characterized by the use of a single wireless technology whose wireless connectivity formed a single wireless topology. Multiple access and other network control protocols—in particular routing—were specifically tailored for operation with that wireless (i.e. link layer) technology. This approach to routing is sometimes referred to as "subnet" or "link layer" routing.

Recently, the continuing advances in computing and communications technologies are yielding relatively high- performance, yet low-cost computing and communication devices (e.g. Bluetooth). In coming years, communication devices utilizing spread-spectrum and other advanced waveforms will become less expensive. In addition, it may become more commercially feasible to develop advanced multi-mode radios and communication devices (e.g. integrated personal digital assistants and cellular phones) which use multiple wireless technologies simultaneously as well. This is being realized today in laboratories using laptop computers as router platforms.

any technical challenges continue to exist at the link and physical layers, specifically in the areas of multiple access, waveform/coding design, quality of service (QoS), and priority scheduling schemes. As a result, *link and physical layer technologies will continue to evolve over time*.

3.2 IP-Based Design Approach

These hardware advancements, coupled with the increasing use of IP technology in both commercial and military systems, are resulting in a shift in design philosophy from closed, proprietary systems to Internet-compatible standards-based systems. The rationale is multifold, including:

- **Routing Flexibility, Efficiency, and Robustness**. When multiple wireless technologies are available in a given mobile network (see Fig. 2), it is desirable that routing occur at the IP layer[2]. The figure gives an example network where each node consists of a mobile router, which has an attached subnet containing one or more IP-addressable hosts and other devices. Some nodes utilize a single wireless device of technology A, others a different wireless device of technology B and some utilize both technologies.

In general, the wireless connectivity, and hence the network topology, corresponding to each wireless technology will be different. Thus, adjacent nodes may be connected by one or between wireless technologies gives added flexibility to the routing algorithm, including more robustness to topological changes and potentially higher performance, especially in highly-dynamic networks. This requires an approach to routing, which is— at some level— *independent* of any given wireless technology.

Hardware Economies of Scale. Wholesale reinvention of network layer technology for each of these underlying technologies is viewed here as somewhat redundant and expensive. As wireless hardware becomes a commodity, the open systems design approach maintains that only the medium access (MAC) and data link layers need directly reflect the characteristics of a given physical layer technology. While it is true that tightly-coupled routing and

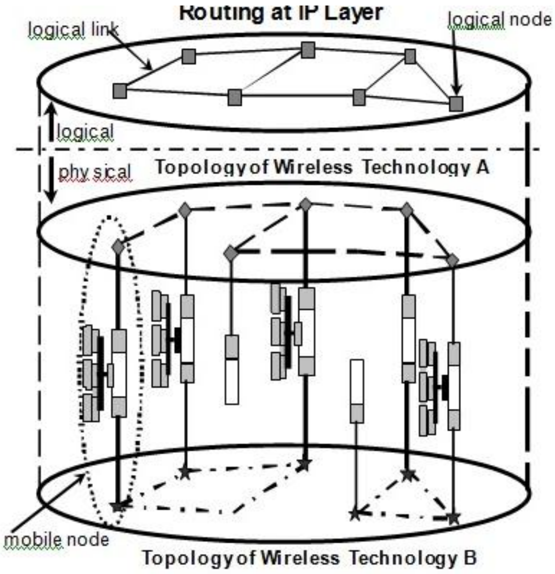


Figure 2: A MANET Consisting of Two Wireless Technologies (A and B), and Their Logical Union Which Forms the *Wireless Fabric* for Routing at the IP layer

both technologies. By routing at the IP layer, it is possible to flexibly, efficiently, and robustly forward a packet through the wireless "fabric" consisting of the logical *union* of the topologies of the individual wireless technologies. In single-technology routing, lack of connectivity might cause packets to be dropped, or restrict the traffic to slower technologies, which may result in higher end-to-end latency. Thus, it can be seen that the ability to dynamically route link layer design for wireless, multihop networks is generally most efficient, it is not clear that a slightly looser coupling between a standardized routing algorithm and a link layer cannot achieve nearly the same level of performance at less cost. It is desirable to have standardized network/link layer interface definitions to ease widespread deployment and heterogeneous operation, and to allow routing at the IP layer that can be used on top of any wireless technology. Sufficient information regarding the link-layer can be made available to the network layer via such standardized interfaces for improved performance whenever possible. A mobile wireless routing fabric may be made up of many different types of wireless links.

Future Quality of Service (QoS) Support.
The characteristics of various wireless technologies wil likely be different (e.g.differingcapacities,multiple access techniques, support for QoS, etc.) and, depending on QoS traffic characteristics, it may be favorable to route certain traffic classes over specific technologies, only resorting to other technologies when necessary. In these cases, IP-layer routing permits route selection or forwarding policies not possible when routing is constrained to a single wireless medium, and facilitates integration with IP QoS mechanisms developed for the fixed Internet.

Military Use of Commercial Technology: Many military mobile tactical networking systems require peer-to-peer networking capability beyond the fixed Internet and its one- hop fringe; distributed, traffic-specific, uni/multicast routing; minimal communications overhead with a scaleable security infrastructure; and seamless interoperability with the fixed Internet, airborne routers, and satellite communications. IP-based internetworking appears to be a cost effective means of interconnecting such a heterogeneous collection of networked devices.

- End-user and application pressure for *seamless* internetworking will continue regardless of the underlying infrastructure and usage mode (fixed, nomadic or mobile);
- The *physical media independence* features of theIP layer are important to supportmobilerouting through heterogeneous wireless fabrics;
- Connectionless datagram forwarding is a *robust, sensible technical approach* for mobile networking;
- Definition of some common routing approaches and interface definitions provides *future flexibility*, and also improves the *cost effectiveness* of deployed systems are important to support mobile routing through heterogeneous wireless fabrics;
- Connectionless datagram forwarding is a *robust, sensible technical approach* for mobile networking;
- Definition of some common routing approaches and interface definitions provides *future flexibility*, and also improves the *cost effectiveness* of deployed systems.

Within the Internet Protocol Suite, *the internetwork protocol and its associated routing protocols are responsible for gluing disparate media and end systems together.* Standardized internetwork layer routing is therefore desirable in mobile networking environments where there is little or no underlying fixed infrastructure, and where both routers and hosts are mobile.

4 MANET ARCHITECTURAL CONCEPTS

The MANET Working Group (WG) [MANET] in the IETF's Routing Area is chartered to provide improved standardized routing and interface definition standards that support self-organizing, mobile networking infrastructures for usage within the Internet Protocol Suite. In so doing, it hopes to lay a foundation for an open, flexible, and extensible architecture for MANET technology. This is a challenging task as there are many issues that must be balanced in these complex systems. While the MANET WG's charter is to standardize routing technology for MANETs, this should be done in a fashion cognizant of and in accordance with an overall architecture well- suited for supporting future mobile Internet standards efforts, and of achieving and maintaining interoperability with the current and likely future Internet. The following discusses the role of MANET technology as part of the larger, emerging mobile Internet, and summarizes developing MANET architectural concepts.

4.1 A Mobile Internet

Conceptually, the emerging "mobile Internet" can be divided into two layers relative to the fixed network, which here are termed the "mobile host" and "mobile router" layers (depicted in Fig. 3). The mobile host layer consists of hosts temporarily attached to routers on the fixed network—termed "fixed routers" (this paradigm is supported by approaches such as [MobileIP] and [DHCP]).

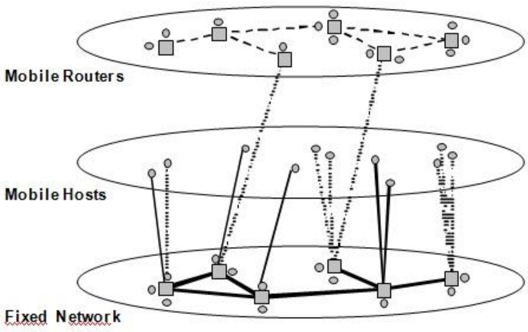


Figure 3: The Emerging *Mobile Internet* (Mobile Host and Mobile Router Layers), and its Relationship with the Traditional Fixed Internet

These hosts are logically "one hop" from a fixed router, and their connections may be wired or wireless. Principal functions handled by this layer are location and address management relative to the fixed network, and the approach requires routing support from the fixed network infrastructure.

The mobile router layer (i.e. MANET technology) consists of mobile routers and mobile hosts, with each mobile host permanently or temporarily affiliated with a mobile router[4]. The mobile router layer need not require routing support from the fixed network, as it forms a mobile infrastructure *parallel* to the fixed infrastructure. Conceptually, one can view the mobile router layer as an alternative to the fixed network layer, albeit a relatively undesirable one due to its relatively low capacity. Because of this it is envisioned that, in the near term, networks in the mobile router layer will operate as "stub" networks from the perspective of the fixed network, carrying only traffic that is either sourced by or destined for a host in the mobile router layer[5]. Also, while the mobile router layer can be viewed *logically* as a unified network parallel to the fixed network, in the near term it will likely be partitioned into separate autonomous systems of mobile routers. It remains to be seen whether future technology advances allow removal of these restrictions, permitting creation of a globally-unified wireless network carrying transit Internet traffic in parallel with the fixed network. Such a network would likely include satellite-based and aerial nodes.

A MANET-attached host (i.e. a host associated with a mobile router, or one which is a mobile router) in the mobile router layer may be in one of two states relative to the fixed network: "disconnected" from the fixed network or "greater than one hop" from the fixed network. When disconnected, the MANET in which the host resides forms an autonomous system *independent* of the fixed network. Otherwise, when connected, *at least one* mobile MANET router is between the mobile host and a fixed router. In other words, the mobile host is directly connected to a MANET router (one hop), and the MANET router is either directly connected to the fixed router (via a second hop), or is indirectly connected to the fixed router through other MANET routers (via multiple hops). Here, the fixed router forms a gateway to the fixed network. In some cases, the gateway router may also be a mobile IP foreign agent, thereby facilitating interoperation with the fixed network via mobile IP. The connection (or hop) between a mobile host and a MANET router may be wired or wireless, whereas the connections (or hops) between MANET routers are generally assumed to be wireless. In the special case where a mobile host *is* a mobile router (e.g. possibly a Bluetooth-enabled Palm Pilot), then the hop between the host and router is only *virtual*.

4.2 MANET Design Approach

The MANET design approach gives future designers maximum *flexibility* in designing MANET control protocols (or policies). Two aspects of the approach are increased vertically-integrated design and addressing.

4.2.1 Increased vertically-integrated design

The traditional, fixed Internet is a network with a multihop topology. So too is the *logical* topology of a MANET as seen in Figure 2, which can essentially be viewed as a "mobile Internet" (only in microcosm) where MANET nodes can be viewed as "mobile subnets". While both networks are resource- constrained, the constraints *differ* in the two environments.

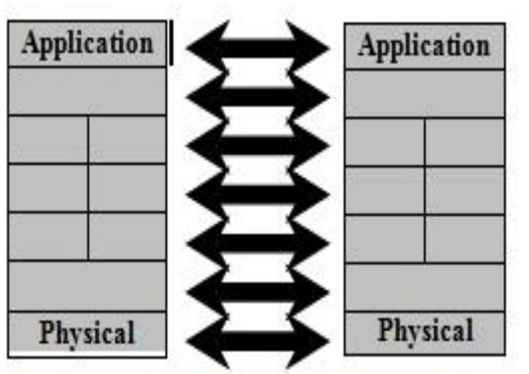
The resource constraints of the fixed Internet (a more "bandwidth abundant" environment) have naturally led to a protocol design approach that favors additional fractional expenditure of bandwidth while minimizing, to the greatest extent possible, the need for processing or storage in routers. This design approach relies on "horizontal" peer-to-peer communication between peer protocol layers on neighboring routers (as shown in Figure 4a), while minimizing the amount of "vertical" interlayer communication within the protocol stack on a given router. This is sometimes referred to as the principle of "strict protocol layer separation". This approach has the added benefit in that it minimizes the degree of fate sharing between adjacent protocol layers, and keeps things simpler in terms of protocol design.

The resource constraints in MANETs are somewhat *opposite* of those in the fixed Internet, and this argues for a different design philosophy—one which minimizes horizontal communication (which expends bandwidth) and increases vertical communication within the protocol stack (see Figure 4b). Protocol stacks designed in this fashion become more "logically-coupled", with increased two-way vertical communication sufficient to permit upper layer protocols to bind more closely with lower layer protocols, thereby removing inefficiencies that might result in additional horizontal communication. Following this approach, upper layer protocols will likely become dependent on lower layer protocols for protocol-specific functionality. This design approach is being followed in the recently proposed multicast algorithms of [LAM, AODV] where the multicast functionality explicitly depends on the underlying unicast algorithm;

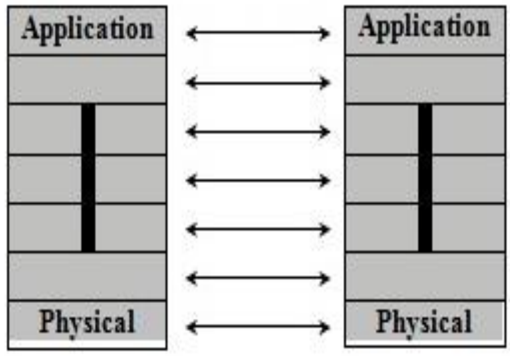
In a similar fashion, network layer protocols may bind more tightly with link layers through extended "rich" interfaces to exploit link layer characteristics for improved performance when possible. Recent MANET proposals [DSR, AODV] recommend utilizing the

Request-To-Send/Clear-To-Send(RTS/CTS) functionality of the IEEE 802.11 standard, when available, to permit efficient link layer detection of neighbor connectivity information. Recent work [Broch98] indicates that this improves the performance and reduces overhead requirements for these protocols.

service interfaces to commonly available link layers such as IEEE 802.11 (and, in the future, possibly Bluetooth) facilitates their use by other designers.



(a) Fixed Internet Protocol Design Approach: emphasize "horizon" of communications to conserve router resources



Of course, this overall design approach emphasizing closer vertical integration runs counter to that of the existing Internet, and the extent to which it can be realized may largely be dictated by economics, simplicity, and interoperability with the existing Internet protocols. Engineering trade-offs must be made. Increases in complexity should be avoided unless significant performance improvements result.

Wireless network enhancements to transport functionality such as TCP, while desirable, may not be feasible if interoperability with the existing network is desired. In this case, the proposed design approach may only be feasible by closely integrating the lowest three layers (yet to be designed) in support of TCP requirements (already deployed). This still leaves the possibility that future transport and application-level protocols can be efficiently designed in an integrated fashion, possibly incorporating Application Layer Framing concepts [ALF].

However, both protocols may still function atop simpler CSM

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5. APPLICATION TO COMMERCIAL AND MILITARY NETWORKING

An earlier section enumerated the perceived benefits of IP- based networking for mobile wireless systems: cost effectiveness, flexibility, interoperability and physical media in Due to the relatively low capacities achievable over mobile, multihop wireless networks, MANET technology is not yet well suited for providing high-speed, wide-area, infrastructure networking functionality. This is because regardless of the flexibility and potential robustness of these systems,

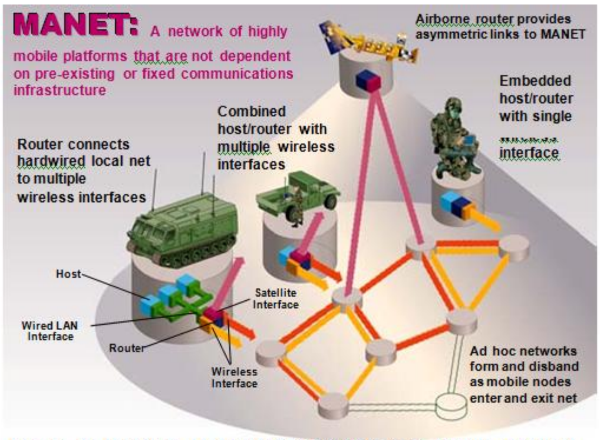

Figure 5: Possible Uses of MANET in Future Mobile Tactical Networks

users typically choose to use the communication technology offering lowest latency and, in the near term, that choice will seldom be MANET technology if any other alternative is available. However, this does not mean that wide spread usage of MANET technology is not possible or will not occur at the edges of the network or wherever no prior infrastructure exists.

5.1 Commercial Networking

MANET technology is likely to find its initial usage in *small* application scopes, where small refers to the number (less than 100) of nodes in the network. Commercially, it is likely to find near-term applications in extending the range of WLAN technology over multiple radio hops. Networks could be built from WLAN technologies such as HIPERLAN and IEEE 802.11 that cover small areas of several square kilometers. These technologies may be also be internetworked using the IETF MANET multi-technology routing approach, so hybrid networks could be built using both technologies. People and vehicles can thus be internetworked in areas without existing communication infrastructure, or when the use of such infrastructure is not desired.

On smaller scales, technologies such as Bluetooth can be exploited in interested ways (perhaps in combination with 802.11-type technology) to build embedded wireless networks. These networks could have a combination of static and mobile nodes (e.g., imagine a network of low-power microsensors and robots) which could be fielded without cabling and with minimal pre-configuration. It is likely that, as computing and communication devices proliferate, unforeseen uses of this technology will emerge, particularly in the embedded systems and micro-networking fields.

5.2 Military Networking

As the Department of Defense moves to a more open standards based distributed information architecture, it must overcome the inherent vulnerabilities of an approach that uses standardizedprotocols and commercial communications technologies, while still addressing the unique robustness issues that arise in the military environment. Large-scale, mobile, multihop wireless networking systems present significant challenges to the designers of IP-based networking as they must operate in an environment with highly mobile nodes and infrastructure; bandwidth-constrained unreliable wireless communications; high levels of interference; electronic and information warfare threats; and a high likelihood of node destruction and capture.

Large scale, mobile infrastructure applications of wireless multihop networking technology are difficult to build, and the military is actively pursuing research and development efforts (e.g. [MMWN]) that feed technology into large-scale mobile systems such as the Near Term Digital Radio [NTDR]. A long- term difficulty with large-scale, wide-area usage of this technology is the relatively low performance achievable over terrestrial, mobile, multihop wireless networks. The minimal latency networking choice may not be a purely terrestrial-based ad hoc network if satellite and aerial platforms are available for use by mobile forces. Rather, a “vertically networked” hybrid system composed of terrestrial, aerial and satellite nodes could best serve mobile users. In the long term, MANET technology appears well suited for internetworking these diverse, hybrid networks.

5.3 Areas for Future Work

For MANET technology to be more easily deployable for military (and civilian) uses, improvements are needed in areas such as high capacity wireless technologies, address and location management, interoperability and security.

Advances in *physical and link layer technologies* are necessary to enable MANETs to carry larger volumes of traffic, and to enable provision of low latency services over longer distances. Current wireless technologies greatly limit both system capacity and the forms of multiple access that may be utilized. Research underway in the areas of multiuser detection and space division multiple access offers the promise of greater spectral and spatial reuse, and higher system capacity as well. When feasible, these techniques may permit the development of affordable multiple access technologies better suited to supporting large-scale, mobile multihop communications.

6. CONCLUSIONS

The networking opportunities for MANETs are intriguing and the engineering tradeoffs are many and challenging. This paper presented a description of ongoing work and a vision for the future integration of mobile networking technology into the Internet. There is a need for standardized, secure, and interoperable routing and interface solution(s) for mobile networking support, which is being pursued through the IETF. The future holds the possibility for deploying inexpensive, IP internetworking compatible solutions to form self-organizing, wireless routing fabrics for commercial and military use.

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