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Internet-based Mobile Ad Hoc Networking

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ABSTRACT[1]

Internet-based 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

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 forward-deployed 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 provides long-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.

1.1 MANET Technology

A Mobile Ad hoc NETwork (MANET) consists of mobile platforms, which are free to move about arbitrarily. Each of these platforms, herein simply referred to as "nodes", logically consists of a router with possibly multiple IP-addressable hosts and multiple wireless communications devices (see Fig. 1). A node may consist of physically separate networked devices (see figure 1b), or may be integrated into a single device such as a laptop or handheld computer (see figure 1c).

The nodes are equipped with wireless transmitters and receivers using antennas which may be omni-directional (broadcast), highly directional (point-to-point), steerable (arrays) or some combination thereof. At a given point in time, depending on the nodes' positions and their transmitter and receiver coverage patterns, transmission power levels, and co-channel interference levels, a wireless connectivity in the form of a dynamic, multihop graph or "ad hoc" network exists between the nodes.

1.2 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 mobile users must work "on the go" changing points of attachment as necessary. In either case, additional networking

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support 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 need. But now, given the fundamental change in the composition of the routing infrastructure (i.e. from fixed, hardwired and bandwidth-abundant to dynamic, wireless and bandwidth-constrained), much of the fixed infrastructure's control technology is no longer useful. Often, there is lower capacity available within the wireless infrastructure and overhead control traffic requirements should be lessened. The infrastructure's routing algorithms and, indeed, much of the networking suite must be reworked to function efficiently and effectively in this mobile environment.

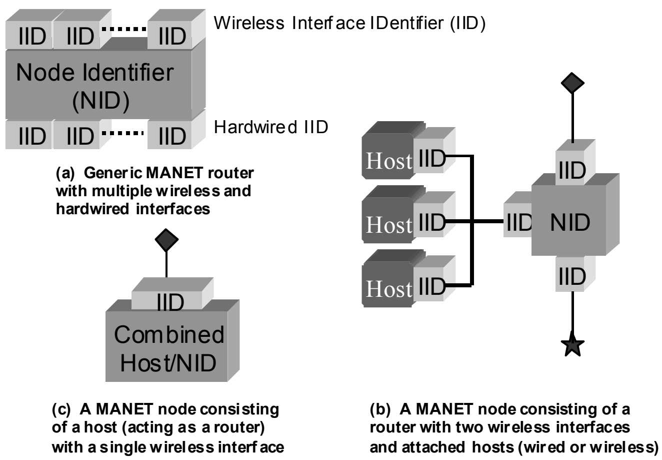

Figure 1: The Generic MANET Router Structure and Two Possible MANET Node Configurations

1.3 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:

- **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**. Mobile wireless networks are generally more prone to information and physical security threats than are fixed, hardwired nets. Existing link layer security techniques are often applied within wireless networks to reduce these threats.

The need for efficiency under these demanding conditions creates a set of underlying assumptions and performance concerns for protocol design that differ from those guiding the design of routing and other network control protocols within the higher-speed, quasi-static topology of the fixed Internet.

2 ADVANTAGES OF IP LAYER ROUTING

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

2.1 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.

Many 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*.

2.2 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 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 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.

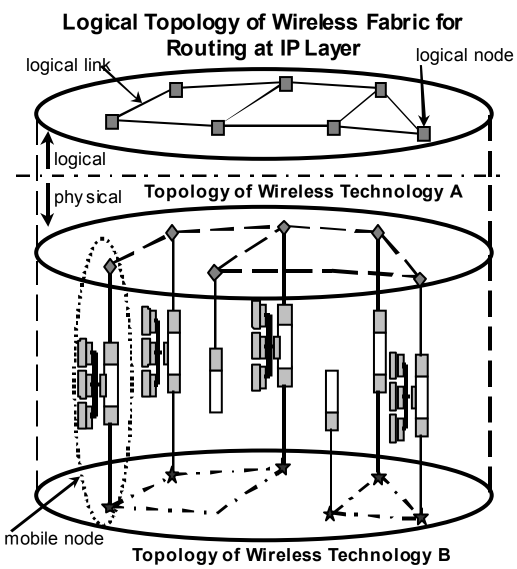

Figure 2: A MANET Consisting of Two Wireless Technologies (A and B), and Their Logical Union Which Forms the *Wireless Fabric* for Routing at the IP layer

- **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 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 and technologies. Such a technical architecture complements mass manufacture of inexpensive wireless devices which could interoperate with each other directly via the link-layer, or indirectly via the IP layer, with the IP-layer routing providing the glue that binds the mobile fabric together.
- **Future Quality of Service (QoS) Support**. The characteristics of various wireless technologies will likely be different (e.g. differing capacities, 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. The future of QoS-capable mobile routing remains largely a research question[3], but the MANET multi-technology architecture leaves open the possibility of such support.
- **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.

Summarizing this section, an *internetwork* layer routing solution for MANETs is important for the following reasons:

[2] It is interesting to note that the topology of a MANET resembles that of the larger Internet --- only in a microcosm. Each mobile node, with its collection of hosts, resembles a subnet and the routers route information between the "mobile subnets" through the wireless fabric.

[3] Some efforts in this direction are [MMWN, ITT, INSIGNIA, CEDAR].

- 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 the IP layer 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.

3 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.

3.1 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]). 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.

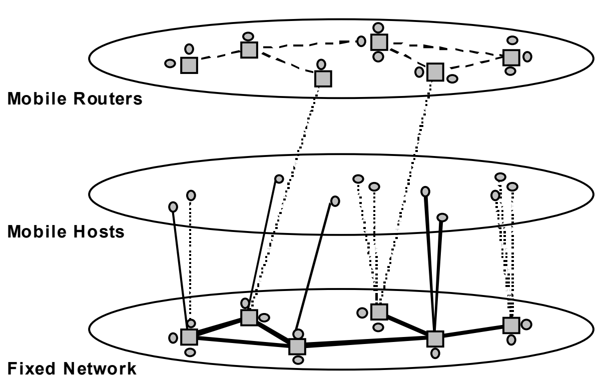

Figure 3: The Emerging *Mobile Internet* (Mobile Host and Mobile Router Layers), and its Relationship with the Traditional Fixed Internet

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*.

3.2 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] In some cases this distinction is only logical, as a single device may be both a mobile host and a mobile router.

[5] Operation in a full-fledged "transit" network would require carrying traffic with both source and destination addresses outside the mobile router layer. This mode of operation significantly increases operational complexity and is considered undesirable in the near term.

3.2.1 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; and in the relationship between [IMEP]—a network layer support protocol—and other protocols [TORA, OLSR] which use IMEP to provide common support functions[6].

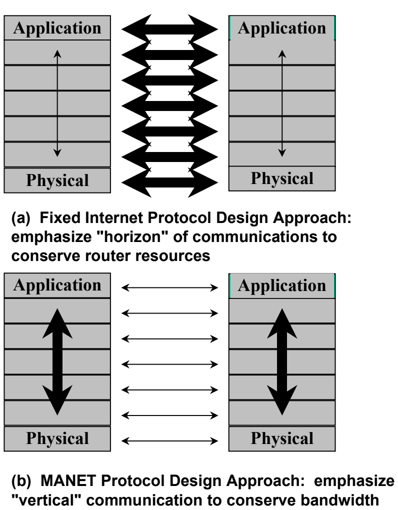

Figure 4: Fixed and MANET Protocol Design Philosophies

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. However, both protocols may still function atop simpler CSMA/CA-based link layers that do not provide this functionality. Development of an IP-to-IEEE 802.11 interface specification would permit future IP-based routing algorithms to more readily utilize the services of 802.11. The development of such IP-standardized service interfaces to commonly available link layers such as IEEE 802.11 (and, in the future, possibly Bluetooth) facilitates their use by other designers.

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].

[6] This approach is not being followed by all MANET designers, however, as numerous proposed multicast approaches are independent of the underlying unicast algorithm [AMRoute, AMRIS, ODMRP, CAMP]. Also, [ZRP] is intended to work with many unicast algorithms during its operation. A design choice being made here is that the increased flexibility is worth any resultant performance loss.

3.2.2 Addressing

While this is still an open issue within the Working Group, a sufficient addressing architecture appears to be one which supports the following capabilities:

1. interoperability via adherence to the IP addressing architecture;
2. simultaneous use of multiple wireless technologies (support for routing through the wireless fabric); and
3. the presence of multiple hosts per router.

These capabilities can be realized by an architecture that:

- identifies end hosts with IP addresses (satisfies capability 1);
- identifies a MANET node with a Node ID (NID) which is *separate* from its Interface IDentifiers (IID) (permits capability 2); and
- allows advertisement of multiple hosts and subnets per MANET node (permits capability 3).

Separation of router and interface identification is similar to the practice already followed in parts of the fixed network (e.g. in [OSPF]), and it appears to be well suited for building a mobile routing infrastructure incorporating the routing fabric concept as well. Note that this approach does not specify *what* the identifiers are, or *how* they are assigned. This is a separable issue, although one which is related to routing. Policies and protocols for router, host and interface identifier assignment will be developed on an as-needed basis. These policies should reflect the nature of a MANET domain and the routing policy in use.

Not all MANET proposals have addressed this issue of interface and router identification. Two approaches which have are [IMEP] and [DSR]. IMEP identifies router and host interfaces with IP addresses (i.e., an IID is an IP address), and identifies a router with a separate identifier known as a Router Identifier (RID) (i.e. a NID is a RID). This approach is borrowed from [OSPF]. In contrast, DSR identifies router interfaces with 7-bit interface indexes (i.e. an IID is an index), and identifies a router/host with an IP address (i.e. a NID is an IP address).

In terms of supporting multiple hosts per router, again, not all proposals have addressed the issue. Two different approaches which do are [TORA], which advertises a set of host and subnet addresses associated with a given Router ID (as obtained from IMEP), and [AODV], which advertises a host address which may optionally be marked as a variable-sized "subnet" address when desired by a subnet group leader.

4 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 independence. These go hand in hand with the view that connectionless datagram forwarding is a robust and sensible technical approach for mobile networking. These views hold for both commercial and military uses of MANET technology.

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, 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.

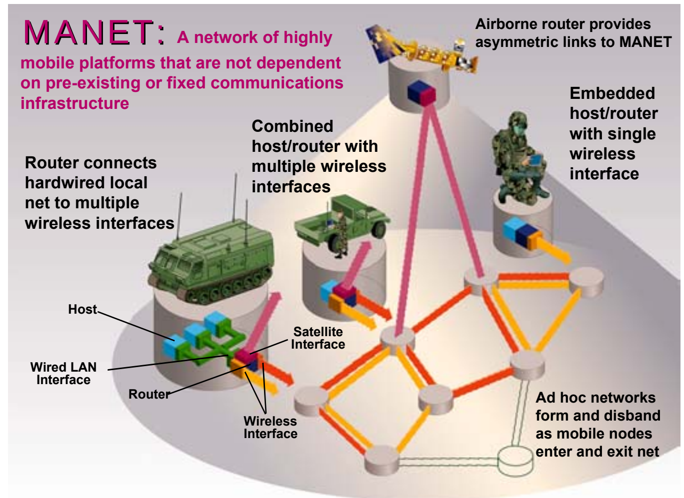

Figure 5: Possible Uses of MANET in Future Mobile Tactical Networks

4.1 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.

4.2 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 standardized protocols 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.

4.3 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.

Challenges exist at the network layer as well. While considerable effort has gone into developing routing technologies for MANETs (and much more is yet to be done), *dynamic IP address and location management* has received much less attention. This may be a side effect of the fact that in fixed networks, addressing between routers is often hand-configured and essentially static, and so is not perceived as a problem equivalent to that of routing. Various research and development efforts have resulted in several possible approaches, but there is no consensus regarding the best policies for this problem, as in many cases it is a domain-specific problem. However, a general framework for self-organizing address management (which can be extended and specialized as desired) is important for applying MANET to tactical networking.

Maintaining *interoperability* with the fixed network, including aerial and satellite platforms, is also a challenge. While MANETs have autonomous capability, it will oftentimes be desirable to connect them to the fixed infrastructure. The prospect of doing so impacts nearly every aspect of network design including addressing, mobility management relative to the fixed network, security and transport layer functionality.

Developing a distributed, scaleable, and bandwidth-efficient *security architecture* that interoperates with the emerging commercial and DoD infrastructure is also a necessary element for eventual widespread utilization of this technology.

5 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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