INTERNET-BASED MOBILE AD HOC NETWORKING

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Internet-based mobile ad hoc networking is an emerging technology that supports self-organizing, mobile networking infrastructures. Essentially a "mobile routing infrastructure," such networks offer several advantages for future commercial and military applications.

Mobile ad hoc networking technology has been under sporadic development for over 20 years. As early as the 1970s, researchers developed related radio-based networking technology commonly referred to as Mobile Packet Radio. Since then, the technology has been applied to other wireless physical layer systems such as diffused infrared. Essentially, mobile ad hoc networking technology enables an autonomous system of mobile nodes. It is well suited for enabling peer-to-peer operation in mobile, forward-deployed military networks. Recently, applicable commercial radio technologies have begun to appear, as have commercial standards efforts such as the ETSI HiperLAN Wireless LAN (WLAN) standard,[1] the IEEE 802.11 WLAN standard,[2] and the recent work within the Bluetooth consortium (http://www.bluetooth.com).

In this article we give an overview of mobile ad hoc networking technology and current Internet Engineering Task Force (IETF) standardization efforts. We describe architectural concepts evolving from the IETF's Mobile Ad Hoc Networks (Manet) Working Group,[3] discuss current limitations of the technology, and raise research issues to be addressed.

MANET: A MOBILE ROUTING INFRASTRUCTURE

Each node in a Mobile ad hoc network (Manet) logically consists of a router with possibly multiple IP-addressable hosts and multiple wireless communications devices (see Figure 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). A set of nodes making up a Manet area is essentially a "mobile routing infrastructure" and can operate in isolation or be connected to the greater Internet via exterior routing functionality.

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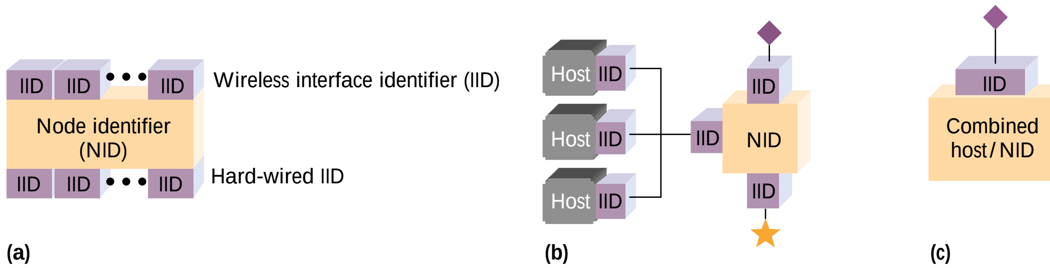

Figure 1. The generic Manet router structure and two possible Manet node configurations: (a) a Manet router with multiple wireless and hard-wired interfaces, (b) a Manet node consisting of a router with two wireless interfaces and attached hosts (wired or wireless), and (c) a Manet node consisting of a host (acting as a router) with a single wireless interface.

The nodes are equipped with wireless transmitters and receivers using antennas that can be omnidirectional (broadcast), highly directional (point-to-point), steerable (arrays), or some combination thereof. At a given point in time, depending on the nodes' positions, 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.

Evolving Mobility

In a Manet, routers can be mobile, and interrouter connectivity can change frequently during normal operation. In contrast, the Internet, like nearly all telecom networks, possesses a quasi-fixed infrastructure consisting of routers or switches that 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 addresses based on their location in a fixed network-addressing hierarchy and oftentimes 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 mobile, meaning that they can change their point of attachment to the fixed infrastructure. This is the paradigm of cellular telephony and its Internet equivalent, mobile IP. In this approach, a user's identity depends upon whether the user adopts a location-dependent (temporary) or location-independent (permanent) identifier.

Users with temporary identifiers are sometimes referred to as nomadic, whereas users with permanent identifiers are referred to as mobile. The distinction is that although nomadic users may move, they carry out most network-related functions in a fixed location. Mobile users, on the other hand, must work "on the go," changing points of attachment as necessary. In either case, additional networking support may be required to track a user's location in the network so that information can be forwarded to its current location using the routing support within the more traditional fixed hierarchy.

Mobile ad hoc networking changes things even more. Now the routing infrastructure can move along with the end devices. Thus the infrastructure's routing topology can change, and the addressing within the topology can change. In this paradigm, an end user's association with a mobile router (its point of attachment) determines its location in the Manet. As before, a user's identity may be temporary or permanent. But now, given the fundamental change in the composition of the routing infrastructure (that is, from fixed, hardwired, and bandwidth-rich to dynamic, wireless, and bandwidth-constrained), much of the fixed infrastructure's control technology is no longer useful. The infrastructure's routing algorithms and, indeed, much of the networking suite must be reworked to function efficiently and effectively in this mobile environment.

Defining Characteristics

Manets are designed to operate in widely varying environments. Forward-deployed military Manets are envisioned as 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. On a still smaller scale are applications of low-power sensor networks and other embedded systems.

Manets have several characteristics that differentiate them from fixed multihop networks.

- *Dynamic topologies.* Because nodes can move arbitrarily, the network topology, which is typically multihop, can change randomly and rapidly. Adjusting transmission and reception parameters such as power can also impact the topology.
- *Bandwidth-constrained, variable capacity, possibly asymmetric links.* Wireless links will continue to have significantly lower capacity than their hardwired counterparts. One effect of these relatively low to moderate link capacities is that congestion is more problematic (that is, aggregate application demands will frequently approach or exceed network capacity). Another effect is that Manets will often operate in heterogeneous wireless environments with significantly varying bandwidth-delay characteristics.
- *Energy-constrained operation.* Some or all of the nodes in a Manet may rely on batteries for 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.

AN ARCHITECTURE FOR MOBILE NETWORKS

The IETF Manet Working Group (chartered within the IETF Routing Area) is working toward producing standardized routing and interface definition standards that support self-organizing, mobile networking within the Internet Protocol Suite.[4] In so doing, it hopes to lay a foundation for an open, flexible, and extensible architecture for Manet technology.

Many issues must be balanced in developing robust, mobile networking systems. While the Manet Working Group's charter is to standardize routing technology for Manets, it must do so in accordance with an overall architecture that supports other future mobile Internet efforts and is interoperable with other developing Internet standards.

Building a "Mobile Internet"

Conceptually, the emerging mobile Internet can be divided into two layers: the *mobile host* and *mobile router* layers (depicted in Figure 2). The mobile host layer consists of hosts temporarily attached to routers on the fixed network, or *fixed routers.* (This approach is supported by standards such as Mobile IP[4] and DHCP.[5]) These hosts are logically one hop

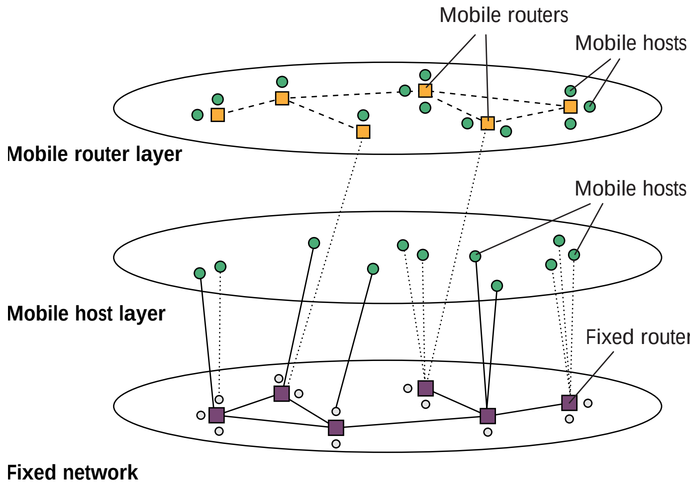

Figure 2. Mobile host and mobile router layers of a mobile ad hoc network (Manet) and their relationships with the traditional fixed Internet.

from a fixed router, and their connections may be wired or wireless. Principal functions handled by these technologies are location and address management. End-to-end operation requires routing support from the fixed network infrastructure.

The mobile router layer (the Manet technology) consists of mobile routers and mobile hosts, with each mobile host permanently or temporarily affiliated with a mobile router (in some cases this distinction is only logical, as a single device may be both a mobile host and a mobile router). The mobile router layer does not require routing support from the fixed network, as it forms a mobile infrastructure parallel to the fixed infrastructure.

The mobile router layer can be seen as an alternative to the more traditional fixed network layer, albeit an undesirable one (when not justified) due to the expected lower achievable capacity. Thus, in the near term, networks in the mobile router layer will likely operate as "stub" networks, carrying traffic that is either sourced by or destined for a host in the mobile router layer. 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. Future technological advances may allow removal of these restrictions, permitting creation of a globally unified wireless network carrying transit Internet traffic parallel to the fixed network. Such a network would likely include satellite-based and aerial nodes.

A Manet-attached host (that is, a host associated with a mobile router, or one that is a mobile router)

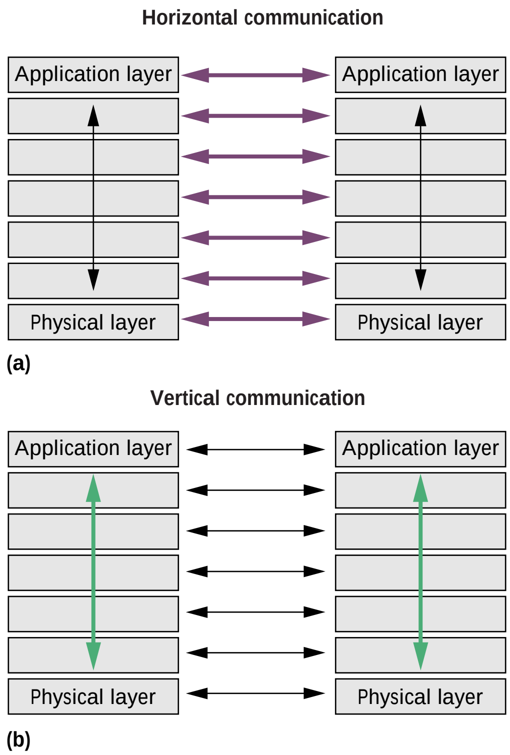

Figure 3. Fixed and Manet protocol design philosophies: (a) the fixed Internet protocol design approach emphasizes the "horizon" of communications to conserve router resources; (b) the Manet protocol design approach increases "vertical" communication to conserve bandwidth.

in the mobile router layer can 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.

Design for Maximum Flexibility

The Internet is a network with a multihop topology. So too is the logical topology of a Manet, as shown in Figure 2. While both networks are resource constrained, the constraints differ in the two environments.

The resource constraints of the 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 protocol layers on neighboring routers (as shown in Figure 3a) 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 benefits of minimizing the degree of fate-sharing between adjacent protocol layers, and simplifying protocol design.

Vertical Communication for Bandwidth Conservation

The resource constraints in Manets are somewhat opposite to those in the fixed Internet, and this argues for a different design philosophy—one that decreases some of the horizontal communication requirements (which expend bandwidth) and increases some of the vertical communication requirements within the protocol stack (see Figure 3b). Protocol stacks designed in this fashion become more logically coupled: the increased two-way vertical communication permits upper-layer protocols to bind more closely with lower-layer protocols, thereby removing some of the inefficiencies that might result in additional horizontal communication.

In a similar fashion, network-layer protocols might bind more tightly with link layers through extended "rich" interfaces, allowing protocols to exploit link-layer characteristics and features for improved performance when possible. Recent Manet proposals[6,7] 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 indicates that this improves the performance and reduces overhead requirements for these protocols.[8] However, both protocols may still function using simpler Carrier Sense Multiple Access/Collision

Avoidance (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 traditional layered design, and the extent to which it can be realized may largely be dictated by economics, simplicity, and interoperability with existing Internet protocols. Engineering trade-offs must be made, and designs that require extreme vertical interaction are undesirable when simplicity and flexibility aspects are considered. 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, more closely integrating the lower layers (e.g., Internet routing and wireless link layer) in support of TCP performance requirements (already deployed) may be sensible. This approach still leaves open the possibility that future transport and application-level protocols can be efficiently designed in an integrated fashion to improve operation over Manet networks.

Construction Issues in Addressing Architectures

While still an open issue within the working group, it is recognized that a sufficient addressing architecture should support the following capabilities:

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

These capabilities can be realized by an architecture that

- identifies end hosts with IP addresses (satisfies the first capability);
- identifies a Manet node with a node ID (NID) separate from its interface identifiers (IID) (permits the second capability); and
- allows advertisement of multiple hosts and subnets per Manet node (permits the third capability).

Separation of router and interface identification is similar to the practice already followed in parts of the fixed network (for example, in the Open Shortest Path First [OSPF[9]] Internet routing protocol), and appears well suited for building a mobile-routing infrastructure that incorporates 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 it 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.

MOBILIZING COMMERCIAL AND MILITARY NETWORKS

Several perceived benefits of IP-based networking for mobile wireless systems—cost effectiveness, flexibility, interoperability, and physical media independence (as described in the sidebar "Advantages of IP-Layer Routing in Mobile Networks" on page 66)—go hand-in-hand with a view that connectionless datagram forwarding is a robust and sensible technical approach for building mobile networks. These general views hold for both commercial and military uses of future Manet technology.

Due to the relatively low capacities achievable over mobile, multihop wireless networks, Manet technology cannot yet provide high-speed, wide-area, infrastructure networking functionality. However, this does not mean that widespread use of Manet technology is not possible or will not occur at the edges of the network or wherever a traditional wired infrastructure is less economical or feasible.

Manet technology will likely first appear in networks consisting of fewer than 100 nodes. Commercially, the technology may be used to extend the range of WLAN technology over multiple radio hops. Networks that cover areas of several square kilometers could be built from WLAN technologies such as HiperLAN and IEEE 802.11. These technologies may also be internetworked using the IETF Manet multitechnology routing approach, so hybrid networks could be built using both technologies. People and vehicles can thus be internetworked in areas without a pre-existing communication infrastructure, or when the use of such infrastructure requires wireless extension.

On smaller scales, technologies like Bluetooth can be exploited in interesting ways (perhaps in combination with 802.11-type technology) to build embedded wireless networks. These networks

ADVANTAGES OF IP-LAYER ROUTING IN MOBILE NETWORKS

Mobile packet radio systems have traditionally 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 typically used a single wireless technology whose connectivity formed a single wireless topology. Multiple access and other network control protocols—in particular routing—were specifically tailored for operation with that wireless (or link-layer) technology, an approach sometimes referred to as *subnet* or *link-layer* routing.

Many technical challenges continue at the link and physical layers (for example, in the areas of multiple access, waveform/coding design, quality of service (QoS), and priority scheduling schemes). However, these technologies will evolve over time, eliminating the usefulness of stovepipe solutions.

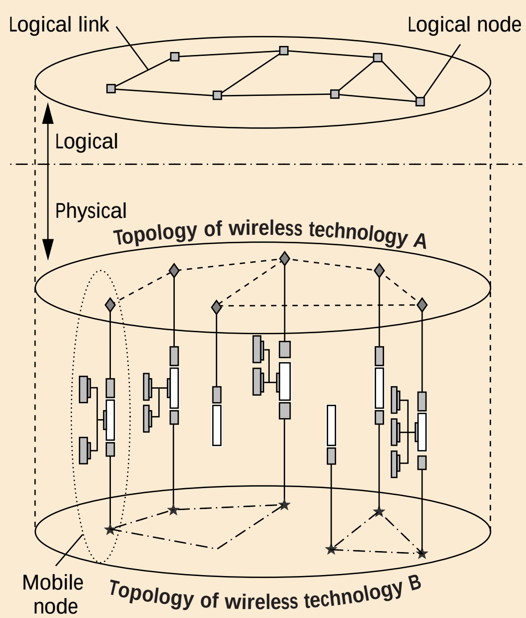

Figure A. A mobile ad hoc network (Manet) consisting of two wireless technologies (A and B) and their logical union, which forms the wireless fabric for routing at the IP layer.

Ongoing advances in electronic hardware are yielding relatively high-performance, yet low-cost computing and communication devices. 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 multimode radios and communication devices (such as integrated personal digital assistants (PDAs) and cellular phones) that use multiple wireless technologies simultaneously. This is being conceptually realized today in laboratories using laptop computers as router platforms.

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

Flexibility

When multiple wireless technologies are available in a given mobile network, it is desirable that routing occur at the IP layer. Figure A shows a network where each node consists of a mobile router with 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 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*—the logical union of the topologies of the individual wireless technologies. The ability to dynamically route between wireless technologies adds flexibility to the routing algorithm, including greater robustness to topological changes and potentially higher performance, especially in highly dynamic networks. This requires an approach to routing that is at some level independent of any given wireless technology.

Interoperability

Wholesale reinvention of network-layer technology for each underlying technology is redundant and expensive. As wireless hardware becomes a commodity, the open-systems

could have a combination of static and mobile nodes (for example, imagine a network of low-power microsensors and robots), which could be fielded without cabling and with minimal preconfiguration. As computing and communication devices proliferate, unforeseen uses of this technology are likely to emerge, particularly in the embedded systems and micronetworking fields.

design approach maintains that only the medium access and data-link layers need directly reflect the characteristics of a given physical-layer technology. While tightly coupled routing and link-layer design for wireless, multihop networks is generally most efficient, a slightly looser coupling between a standardized routing algorithm and a link layer may achieve nearly the same level of performance at a lower overall cost.

Standardized network/link-layer interface definitions can ease widespread deployment and heterogeneous operation. Such interfaces also allow IP-layer routing technology to be re-used on top of many wireless technologies. Sufficient information regarding the link layer can be made available to the network layer via such interfaces.

A mobile wireless routing fabric can be made up of many different types of wireless links and technologies. Such a technical architecture complements mass manufacture of inexpensive wireless devices that 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 QoS Support

Wireless technologies will likely vary (for example, they will have differing capacities, multiple access techniques, and support for QoS), and, depending on QoS traffic characteristics, it may be favorable to route certain traffic classes over preferred interface technologies, resorting to other less preferable technologies (such as lower capacity or higher power consumption) only 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; it also facilitates integration with IP QoS mechanisms developed for the fixed Internet. Although the future of QoS-capable mobile routing remains largely a research question, the Manet multitechnology architecture may prove to offer support in this area.

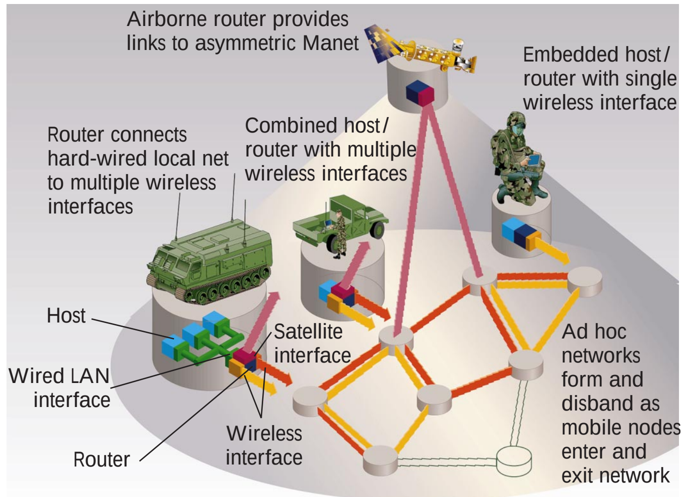

Figure 4. Possible uses of Manet in future mobile tactical networks.

Large-scale, mobile, multihop wireless networking systems present many challenges to the designers of IP-based networking. Such systems must operate in environments with highly mobile nodes, bandwidth-constrained unreliable wireless communications, high levels of interference, and accompanying potential electronic information threats. One additional challenge with potential large-scale, wide-area use of this technology is the relatively low performance achievable over "strictly 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 also available for routing use by mobile nodes. Rather, a "vertically networked" hybrid system composed of terrestrial, aerial, and satellite nodes may best serve mobile users (see Figure 4). In the long term, Manet technology appears well suited for internetworking these diverse, heterogeneous networks.

AREAS FOR FUTURE WORK

Before Manet technology can be easily deployed in military and civilian applications, improvements must be made in such areas as high-capacity wireless technologies, address and location management, interoperability, and security.

Further advances in physical and link-layer technologies will enable Manets to carry larger volumes of traffic and provide low-latency services over longer distances. Current wireless technologies greatly limit both system capacity and the forms of multiple access that can be utilized. Research underway in the areas of multiuser detection and space-division multiple access promises greater spectral and spatial reuse, as well as higher system capacity. 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, dynamic IP address and location management has received much less attention. This may be because 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, as in many cases the problem is domain-specific. However, a general framework for self-organizing address management (which can be extended and specialized as desired) is important for applying Manet to more general self-organizing networks.

Maintaining interoperability with the fixed network, including aerial and satellite platforms, is also a challenge. While Manets are autonomous, it will oftentimes be desirable to interconnect 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, scalable, and bandwidth-efficient security architecture that interoperates with the emerging commercial and DoD infrastructure is also necessary for eventual widespread utilization of this technology. ■

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