INVITED COMMENTARY

A BRIEF OVERVIEW OF AD HOC NETWORKS: CHALLENGES AND DIRECTIONS

RAM RAMANATHAN AND JASON REDI
BBN TECHNOLOGIES

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One of the most vibrant and active "new" fields today is that of ad hoc networks. Significant research in this area has been ongoing for nearly 30 years, also under the names packet radio or multi-hop networks. Within the past few years, though, the field has seen a rapid expansion of visibility and work due to the proliferation of inexpensive, widely available wireless devices and the network community's interest in mobile computing.

An ad hoc network is a (possibly mobile) collection of communications devices (nodes) that wish to communicate, but have no fixed infrastructure available, and have no pre-determined organization of available links. Individual nodes are responsible for dynamically discovering which other nodes they can directly communicate with. A key assumption is that not all nodes can directly communicate with each other, so nodes are required to relay packets on behalf of other nodes in order to deliver data across the network. A significant feature of ad hoc networks is that rapid changes in connectivity and link characteristics are introduced due to node mobility and power control practices. Ad hoc networks can be built around any wireless technology, including infrared and radio frequency (RF).

Ad hoc networking is a multi-layer problem. The physical layer must adapt to rapid changes in link characteristics. The multiple access control (MAC) layer needs to minimize collisions, allow fair access, and semi-reliably transport data over the shared wireless links in the presence of rapid changes and hidden or exposed terminals. The network layer needs to determine and distribute information used to calculate paths in a way that maintains efficiency when links change often and bandwidth is at a premium. It also needs to integrate smoothly with traditional, non ad hoc-aware internetworks and perform functions such as auto-configuration in this changing environment. The transport layer must be able to handle delay and packet loss statistics that are very different than wired networks. Finally, applications need to be designed to handle frequent disconnection and reconnection with peer applications as well as widely varying delay and packet loss characteristics.

Ad hoc networks are suited for use in situations where infrastructure is either not available, not trusted, or should not be relied on in times of emergency. A few examples include: military solders in the field; sensors scattered throughout a city for biological detection; an infrastructureless network of notebook computers in a conference or campus setting; the forestry or lumber industry; rare animal tracking; space exploration; undersea operations; and temporary offices such as campaign headquarters.

HISTORY

The history of ad hoc networks can be traced back to 1972 and the DoD-sponsored Packet Radio Network (PRNET), which evolved into the Survivable Adaptive Radio Networks (SURAN) program in the early 1980s [1]. The goal of these programs was to provide packet-switched networking to mobile battlefield elements in an infrastructureless, hostile environment (soldiers, tanks, aircraft, etc., forming the nodes in the network).

The PRNET used a combination of ALOHA and CSMA approaches for medium access, and a kind of distance-vector routing. SURAN significantly improved upon the radios (making them smaller, cheaper, power-thrifty), scalability of algorithms, and resilience to electronic attacks. The routing protocols were based on hierarchical link-state and were highly scalable.

In the early 1990s a spate of new developments signaled a new phase in ad hoc networking. Notebook computers became popular, as did open-source software, and viable communications equipment based on RF and infrared. The idea of an infrstructureless collection of mobile hosts was proposed in two conference papers [2, 3], and the IEEE 802.11 subcommittee adopted the term "ad hoc networks." The concept of commercial (non-military) ad hoc networking had arrived. Other novel non-military possibilities were suggested (as mentioned in the introduction), and interest grew.

At around the same time, the DoD continued from where it left off, funding programs such as the Global Mobile Information Systems (GloMo), and the Near-term Digital Radio (NTDR). The goal of GloMo was to provide office-environment Ethernet-type multimedia connectivity anytime, anywhere, in handheld devices. Channel access approaches were now in the CSMA/CA and TDMA molds, and several novel routing and topology control schemes were developed. The NTDR used clustering and link-state routing, and self-organized into a two-tier ad hoc network. Now used by the US Army, NTDR is the only "real" (non-prototypical) ad hoc network in use today.

Spurred by the growing interest in ad hoc networking, a number of standards activities and commercial standards evolved in the mid to late '90s. Within the IETF, the Mobile Ad Hoc Networking (MANET) working group was born, and sought to standardize routing protocols for ad hoc networks. The development of routing within the MANET working group and the larger community forked into reactive (routes on-demand) and proactive (routes ready-to-use) routing protocols [4]. The 802.11 subcommittee standardized a medium access protocol that was based on collision avoidance and tolerated hidden terminals, making it usable, if not optimal, for building mobile ad hoc network prototypes out of notebooks and 802.11 PCMCIA cards. HIPERLAN and Bluetooth were some other standards that addressed and benefited ad hoc networking.

Cellular network	Ad hoc network
Fixed, pre-located cell sites and base stations.	No fixed base stations, very rapid deployment.
Static backbone network topology.	Highly dynamic network topologies with multi-hop.
Relatively benign environment and stable connectivity.	Hostile environment (losses, noise) and sporadic connectivity.
Detailed planning before base stations can be installed.	Ad hoc network automatically forms and adapts to changes.

TABLE 1. *Differences between ad hoc and cellular networks.*

OPEN PROBLEMS

Despite the long history of ad hoc networking, there are still quite a number of problems that are open. Particularly among ad hoc networks designed for the military, scalability is one of the most important open problems. Scalability in ad hoc networks can be broadly defined as whether the network is able to provide an acceptable level of service to packets even in the presence of a large number of nodes in the network. As in wired networks, this capability is closely related as to how quickly network protocol control overhead increases as a function of an increase in the number of nodes and link changes. In proactive networks, scalability is often accomplished by introducing routing and/or location hierarchy in the network [5], or by limiting the scope of control updates to locations close to the changes [6, 7]. In reactive ad hoc networks, techniques such as dynamically limiting the scope of route requests and attempting local repairs to broken routes are often used.

Since ad hoc networks do not assume the availability of a fixed infrastructure, it follows that individual nodes may have to rely on portable, limited power sources. The idea of energy-efficiency therefore becomes an important problem in ad hoc networks. Surprisingly, there has been little published work in the area of energy-efficiency of ad hoc networks until fairly recently. Most existing solutions for saving energy in ad hoc networks revolve around the reduction of power used by the radio transceiver. At the MAC level and above, this is often done by selectively sending the receiver into a sleep mode, or by using a transmitter with variable output power (and proportionate input power draw) and selecting routes that require many short hops, instead of a few longer hops [8].

The ability of fixed, wireless networks to satisfy quality of service (QoS) requirements is another open problem. Ad hoc networks further complicate the known QoS challenges in wireline networks with RF channel characteristics that often change unpredictably, along with the difficulty of sharing the channel medium with many neighbors, each with its own set of potentially changing QoS requirements. Reflecting the multi-layer nature of ad hoc networks, there are numerous attempts to improve the QoS problems from the service contracts [9] to the MAC layer. A promising method for satisfying QoS requirements is a more unified approach of cross-layer or vertical-layer integration. The idea is to violate many of the traditional layering styles to allow different parts of the stack to adapt to the environment in a way that takes into account the adaptation and available information at other layers.

A similar multi-layer issue is that of security in ad hoc networks [10]. Since nodes use the shared radio medium in a potentially insecure environment, they are susceptible to denial of service (DoS) attacks that are harder to track down than in wired networks. Also, since a large portion of the network nodes will be dynamically reorganizing and forwarding packets on behalf of others, ad hoc networks are particularly susceptible to the injection of bogus network control traffic. Finally, ad hoc networks can be victims of specialized kinds of security attacks such as DoS attacks that cause a node to use its transceiver so much that it depletes its battery.

A newly emerging challenge is the design of ad hoc networks that can take advantage of the properties of new hardware technologies. One example is that of smart (beamforming) antennas. As in cellular networks, the ability to focus or steer RF energy can provide increased throughput and reduced delay through an increase in spatial reuse [11]. However, most protocols have been designed for omni-directional antennas, resulting in inefficiencies or even failure when used with beamforming antennas.

Robots and sensors also provide new hardware capabilities ripe for new methods of enhancing ad hoc efficiency. Robots, for example, have a tight integration between the processes of movement, decision-making, and networking that allow them to modify their actions while taking into account the effects on many different system aspects [12]. Similarly, sensors are often deployed in a way that makes their roles and capabilities redundant, suggesting new ways of combining application knowledge of delivered information with the routing layer [13].

Finally, a problem that overarches all these others is the lack of well defined and widely accepted models for RF path attenuation, mobil-

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ity, and traffic. These tightly interrelated models are needed for quantifying and comparing ad hoc system performance to a common baseline. The physical processes of refraction, reflection, and scattering of RF radiation is moderately well understood but difficult to quantify in detail when including a large number of complex objects such as foliage, cars, or buildings. In contrast, the pattern of movement of the nodes and the flow of traffic can certainly be easily described in detail, but the dependency on the target application, the lack of existing systems available for study, and the likely interactions between connectivity, movement, and user applications, causes these models to be ill-defined.

THE FUTURE

Imagine the following scenarios: a wireless mesh of rooftop-mounted ad hoc routers; an ad hoc network of cars for instant traffic and other information; sensors and robots forming a multimedia network that allows remote visualization and control; multiple airborne routers (from tiny robots to blimps) automatically providing connectivity and capacity where needed (e.g., at a football game); an ad hoc network of spacecraft around and in transit between the Earth and Mars.

These may seem like science fiction, but are in fact ideas pursued seriously by the ad hoc research community. While only time can tell which of these imagined scenarios will become real, the above offers a glimpse into both the technological potential and the evolving state of the art. We discuss in this section the forces at play that are likely to shape the future of ad hoc networking, and discuss the directions in which it may evolve.

To appreciate the role ad hoc networks are likely to play in the future, consider this: bandwidth-hungry applications and the laws of physics drive wireless architectures away from cellular toward ad hoc. This is because more capacity implies the need for a higher communications bandwidth and better spatial spectral reuse. Higher bandwidth is found at higher frequencies, where the propagation is dismal. Further, mobile devices have to be power-thrifty. Propagation, spectral reuse, and energy issues support a shift away from a single long wireless link (as in cellular) to a mesh of short links (as in ad hoc networks). That this might be the wave of the future is attested to by burgeoning startups, e.g., Rooftop Communications (now part of Nokia), Mesh Networks, and Radiant Networks, that use a "multihop mesh-based" architecture in place of conventional 3G architectures.

The other main impetus to ad hoc networks comes from the rapidly improving communications technologies. Wireless communication devices are getting smaller, cheaper, more sophisticated, and hence more ubiquitous. Exploitation of these technologies for better ad hoc networking gives rise to new problems that point to new research. For instance, the use of smart antennas in ad hoc networking requires new medium access and neighbor discovery protocols. The ability to dynamically alter spread spectrum codes, modulation schemes, and waveforms require corresponding innovations at the higher layers. Software radios, which represent an important change in radio architecture, offer more flexibility that is suitable for ad hoc networks.

How are ad hoc networks likely to evolve? It is likely that the nodes themselves will be smaller, cheaper, more capable and probably conformal, and come in all forms. Indoor ad hoc networks (perhaps based on Bluetooth, Wireless LAN, or similar technologies) will probably be used to connect smart appliances to the Internet. Mesh-based last-mile solutions will increase in popularity and may even be the dominant solution. Military ad hoc networks will have higher capacities and support multimedia applications, be more adaptive, stealthy, and evolve toward a system where all battlefield elements, mobile or stationary, are multimedia-networked.

Finally, there is the utopian idea of a "global infosphere" where all network elements form a gigantic ad hoc wireless network using unlicensed spectrum, bypassing the existing infrastructure. While fascinating from a research viewpoint, the realization of this vision will depend not only on overcoming the capacity and other hurdles, but also the pragmatics of a "cooperative" network. Notwithstanding our predictions, however, like the Internet, which existed for more than 20 years before the World Wide Web came along, it may be a surprise "killer app" that shapes the future of ad hoc networking.

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