Mesh Networks: Commodity Multihop Ad Hoc Networks

Raffaele Bruno, Marco Conti, and Enrico Gregori, National Research Council (CNR)

ABSTRACT

In spite of the massive efforts in researching and developing mobile ad hoc networks in the last decade, this type of network has not yet witnessed mass market deployment. The low commercial penetration of products based on ad hoc networking technology could be explained by noting that the ongoing research is mainly focused on implementing military or specialized civilian applications. On the other hand, users are interested in *general-purpose* applications where high bandwidth and open access to the Internet are consolidated and cheap commodities. To turn mobile ad hoc networks into a commodity, we should move to more pragmatic "opportunistic ad hoc networking" in which multihop ad hoc networks are not isolated self-configured networks, but rather emerge as a flexible and low-cost extension of wired infrastructure networks coexisting with them. Indeed, a new class of networks is emerging from this view: *mesh networks*. This article provides an overview of mesh networking technology. In particular, starting from commercial case studies we describe the core building blocks and distinct features on which wireless mesh networks should be based. We provide a survey of the current state of the art in off-the-shelf and proprietary solutions to build wireless mesh networks. Finally, we address the challenges of designing a high-performance, scalable, and cost-effective wireless mesh network.

INTRODUCTION

Mobile (multihop) ad hoc networks (MANETs) are collections of mobile nodes connected together over a wireless medium. These nodes can freely and dynamically self-organize into arbitrary and temporary ad hoc network topologies, allowing people and devices to seamlessly internetwork in areas with no preexisting communication infrastructure (e.g., disaster recovery and battlefield environments). The ad hoc networking concept is not new, having been around in various forms for over 30 years — packet radio network (1972), survivable adaptive radio network (1980), global mobile information system (early 1990s). Traditionally, tactical networks have been the only communication networking application that followed the ad hoc paradigm. Recently, the introduction of low-cost wireless technologies (e.g., Bluetooth and IEEE 802.11), together with the standardization efforts of the Internet Engineering Task Force (IETF) MANET Working Group, have been generating renewed and growing interest in research and development of MANETs outside the military field. Indeed, by scanning the literature we can find thousands of research papers related to multihop ad hoc networks [1]. IETF MANET WG is standardizing four routing protocols, and 802.11 wireless cards are ubiquitous (an enabling technology for civilian MANETs). However, this type of network does not yet have an impact on our way of using wireless networks. Users seldom operate 802.11 in ad hoc mode and, except in laboratory testbeds, never use multihop ad hoc networks. This has opened a debate in the scientific community on why, after almost a decade of research into ad hoc networking, MANET technology has not yet affected our way of using wireless networks. A common answer is emerging:[1] most of the ongoing research on mobile ad hoc networks is driven by either Department of Defense (DoD) requirements (large-scale military applications with thousands of ad hoc nodes) or specialized civilian applications (disaster recovery, planetary exploration, etc). DoD generated a research agenda and requirements that are far from real users' requirements. Indeed, military and specialized civilian applications require lack of infrastructure and instant deployment. They are tailored to very specialized missions, and their cost is typically not a main issue. On the other hand, from the users' standpoint, scenarios consisting of a limited number of people wanting to form an ad hoc network for sharing some information or access to the Internet are much more interesting. In this case, users are looking for multipurpose networking platforms in which cost is an issue and Internet access is a must. To turn MANETs into a commodity some changes to the original MANET definition would seem to be required. By relaxing one of the main constraints of MANETs, "the network is made of users devices only and no infrastructure exists," we move to a more pragmatic "opportunistic ad hoc networking" in which multihop ad hoc networks are not isolate self-configured networks, but

[1] *See, for example, Mario Gerla in the IEEE MASS 2004 panel, and Victor Bahl's opening talk at the Mesh Networking Summit 2004.*

Several public transportation companies, government agencies, and research organizations are looking for viable solutions to realize intelligent transport systems (i.e., integrated public transportation systems that are built to be safe, cost effective, efficient, and secure).

rather emerge as a flexible and low-cost extension of wired infrastructure networks, coexisting with them. Indeed, a new class of networks is emerging from this view: *mesh networks* [2]. Mesh networks are built on a mix of fixed and mobile nodes interconnected via wireless links to form a multihop ad hoc network. As in MANETs, users' devices are an active part of the mesh. They dynamically join the network, acting as both user terminals and routers for other devices, consequently further extending network coverage. Mesh networks thus inherit many results from MANET research but have civilian applications as the main target. Furthermore, while the MANET development approach was mainly simulation-based, from the beginning mesh networks have been associated with real testbeds. By designing/implementing "good enough" solutions it has been possible to verify the suitability of this technology for civilian applications and stimulate users' interest in adopting it. Even though mesh networks are quite recent, they have already shown great potential in the wireless market. Indeed, we can subdivide mesh networks into two main classes: off-the-shelf and proprietary solutions. An example of the first class are so-called *community networks* built (mainly) on 802.11 technology and aimed at providing Internet access to a community of users that can share the same Internet access link [3]. Some examples of this are Seattle Wireless, Champaign-Urbana Community Wireless Network (CUWiN), San Francisco BAWUG, and the Roofnet system at MIT (MIT Roofnet). On the other hand, several companies are now selling interesting solutions that exploit the mesh network potential for indoor and/or outdoor applications (e.g., MeshNetworks, Tropos Networks, Radiant Networks, Firetide, BelAir Networks, Strix Systems).[2] For example, indoor mesh networks can be set up by wireless interconnected access points that, by exploiting routing algorithms developed for MANETs, can create extended WLANs without a wired infrastructure. Outside buildings, mesh networks can be used to provide wireless access across wide geographic areas by minimizing the number of *wired* ingress/egress points toward the Internet. Outdoor networks might be used, for example, by municipalities to extend their wired networks wirelessly.

This promising networking technology recently received a further boost when IEEE 802 creating Task Group 802.11s aimed at defining medium access control (MAC) and PHY layers for mesh networks to improve wireless LAN (WLAN) coverage with no single point of failure. In such networks, 802.11 access points relay information from one to another, hop by hop, in router-like fashion. As users and access points are added, capacity is added. In addition to 802.11s, other IEEE Working Groups are currently working to provide mesh networking extensions to their standards (e.g., 802.15.5, 802.16a, and 802.20).

The aim of this article is to provide a survey of this promising emerging technology. First, we will present some popular commercial applications for wireless mesh networks, exemplifying its potentialities. We introduce a general architecture for mesh networks, highlighting the benefits of this radically new networking paradigm. Then we sketch off-the-shelf and proprietary solutions for building mesh networks, respectively. We review the standardization efforts currently ongoing to introduce mesh networking functionalities in IEEE 802-based wireless technologies. We discuss the main research challenges of building scalable and high-performance mesh networks.

Popular Commercial Applications for Wireless Mesh Networks

Several emerging and commercially interesting applications for commodity networks based on wireless mesh network architecture have been deployed recently. To identify all possible applications exploiting the mesh networking paradigm would be too ambitious for the scope of this survey. Consequently, in this section we focus on providing case studies that benefit from wireless mesh networks (i.e., concrete and operating implementations of mesh networking that exemplify the potential behind this radically new framework).

Intelligent Transportation Systems

Several public transportation companies, government agencies, and research organizations are looking for viable solutions to realize *intelligent transport systems* (i.e., integrated public transportation systems that are built to be safe, cost effective, efficient, and secure). Wireless mesh could be the flexible solution to implement the information delivery system required to control transportation services, as depicted in Fig. 1a. An example for this application scenario is the Portsmouth Real-Time Travel Information System (PORTAL), a system that, as part of a citywide public transportation communications network, aims at providing real-time travel information to passengers.[3] This system is realized by equipping more than 300 buses with mesh technology provided by MeshNetworks Inc. The wireless mesh network allows anybody to display, at more than 40 locations throughout the city, real-time information on transportation services, such as where his/her bus is, its ultimate destination, and when it is scheduled to arrive. The same system is also expected to be used to address and alleviate transportation congestion problems, control pollution, and improve transportation safety and security.

Public Safety

The 9/11 events have dramatically increased interest in *public safety* (police, fire departments, first responders, and emergency services), creating additional demand and urgency for wireless network connectivity to provide mobility support, reliability, flexibility, and high bandwidth. For years, solutions based on cellular technologies have been used, but they have proved to be unsatisfactory in many aspects. In particular, cellular data networks promise near ubiquitous coverage and allow high-mobility speeds, but data rate is limited, even lower than a typical dialup connection, and the network infrastructure is extremely

[2] *For an exhaustive list of Web links related to ad hoc and wireless mesh networks, the reader could refer to http://www.antd.nist.gov/wctg/manet/adhoclinks*

[3] *http://www.portsmouth.gov.uk/*

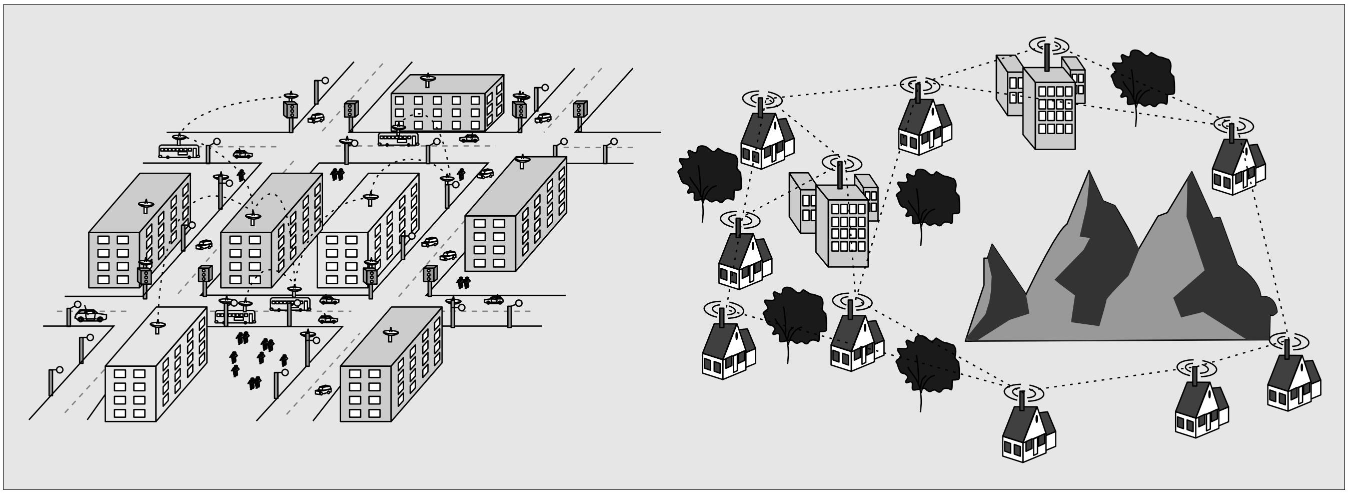

Figure 1. *Emerging commercial applications for wireless mesh networks: a) intelligent transportation system (ITS); b) residential broadband access for hard to reach and/or scarcely populated areas.*

costly. Wireless mesh networks appear to be the natural solution to address the needs of law enforcement agencies and city governments. Currently, several mesh networks are operating to provide public safety applications. For instance, the San Matteo Police Department in the San Francisco Bay Area has equipped all its patrol cars with laptops, and motorcycle and bicycle patrols with PDAs, employing standard 802.11b/g wireless cards for communications. The outdoor wireless network is built using mesh networking technology provided by Tropos Networks. More than 30 Tropos Wi-Fi access points were installed throughout downtown to provide ubiquitous coverage to the zone. Tropos proprietary software components are installed over the access points, providing self-discovery and self-configuring functionalities, communications privacy, and centralized network management and control.

Public Internet Access

Internet service providers (ISPs) are avidly seeking integrated solutions to implement *public Internet access*, which could simultaneously target the markets of residential, business, and travel. A growing number of both small and big ISPs are deploying solutions based on Wi-Fi technologies to provide broadband wireless Internet access. The wireless mesh networks are the ideal solution to provide both indoor and outdoor broadband wireless connectivity in urban, suburban, and rural environments without the need for extremely costly wired network infrastructure. An example of this is the metro-scale broadband city network activated on April 2004 in the city of Cerritos, California, operated by Aiirmesh Communications Inc., a wireless ISP (WISP) company. This network is built up with Tropos-based mesh technology and covers a city area as large as eight square miles using more than 130 outdoor access points, less than 20 percent of them directly connected to a wired backhaul network. This significant reduction of network installation costs ensures rapid deployment of a metropolitan broadband network that is cost effective even with a limited potential subscriber base, as found in rural or scarcely populated urban areas (Fig. 1b).

System and Network Architectures for Wireless Mesh Networks

Wireless mesh has been envisioned as the economically viable networking paradigm to build up broadband and large-scale wireless commodity networks [3]. In this section we extensively elaborate on this vision to identify the unique and distinct characteristics of this new network architecture.

Several "flavors" of mesh network architectures have been conceived by both industry and academia. However, core building blocks and distinct features may easily be identified in mesh architecture. A wireless mesh network is a *fully wireless* network that employs *multihop* communications to forward traffic en route to and from wired Internet entry points. Different from *flat* ad hoc networks, a mesh network introduces a *hierarchy* in the network architecture with the implementation of dedicated nodes (called *wireless routers*) communicating among each other and providing wireless transport services to data traveling from users to either other users or access points (access points are special wireless routers with a high-bandwidth wired connection to the Internet backbone). The network of wireless routers forms a *wireless backbone* (tightly integrated into the mesh network), which provides multihop connectivity between nomadic users and wired gateways. The meshing among wireless routers and access points creates a wireless *backhaul* communication system, which provides each mobile user with a low-cost, high-bandwidth, and seamless multihop interconnection service with a limited number of Internet entry points and with other wireless mobile users. Roughly and generally speaking, backhaul is used to indicate the service of forwarding traffic from the originator node to an access point from which it can be distributed over an external network. Specifically in the mesh case, the traffic is originated in the users' devices, traverses the wireless backbone, and is distributed over the Internet network. To summarize, Fig. 2 illustrates the mesh network archi-

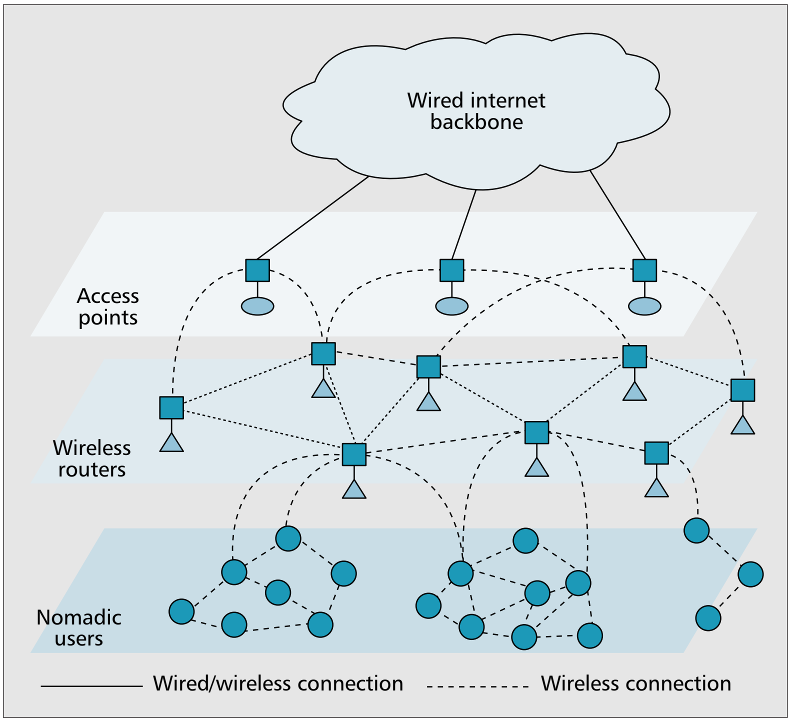

Figure 2. *A three-tier architecture for wireless mesh networks.*

tecture, highlighting the different components and system layers.

The mesh network architecture addresses the emerging market requirements for building wireless networks that are highly scalable and cost effective, offering a solution for the easy deployment of high-speed ubiquitous wireless Internet. In the remainder of this section we further elaborate on the major noticeable benefits of wireless mesh networks that provide substantial arguments in favor of the above claim. The following is not necessarily an exhaustive list of all the possible benefits, but represents an extensive discussion on the motivations behind the mesh networking vision. The interested reader could refer to the Microsoft Mesh Networking Summit 2004[4] for a thorough discussion of mesh networking benefits and challenges.

Reduction of installation costs. Currently, one of the major efforts to provide wireless Internet beyond the boundaries of indoor WLANs is through the deployment of Wi-Fi hot spots. Basically, a hot spot is an area that is served by a single WLAN or a network of WLANs, where wireless clients access the Internet through an 802.11-based access point. To ensure almost ubiquitous coverage in a metro-scale area, it is necessary to deploy a large number of access points due to the limited distance covered by the 802.11 signal. The downside of this solution is an unacceptable increase in the infrastructure costs because a cabled connection to the wired backbone is needed for every access point. Installing the necessary cabling infrastructure not only slows down hot spot implementation, but also significantly increases installation costs. As a consequence, the hot spot architecture is costly, unscalable, and slow to deploy. On the other hand, building a mesh wireless backbone enormously reduces the infrastructural costs because the mesh network needs only a few points of connection to the wired backbone.

Large-scale deployment. In recently standardized WLAN technologies (i.e., 802.11a and 802.11g), increased data rates have been achieved by using more spectrally efficient modulation schemes. However, for a specific transmit power, shifting toward more efficient modulation techniques reduces coverage (i.e., the further from the access point, the lower the data rate available). Moreover, for a fixed total coverage area, more access points should be installed to cover small-size (e.g., pico) cells [3]. Obviously, this picocellularization of WLANs further hinders the scalability of this technology, especially in outdoor environments. On the other hand, multihop communications offers long distance communications via hopping through intermediate nodes. Since intermediate links are short, these transmissions could be at high data rates, resulting in increased throughput compared to direct communications. Moreover, the wireless backbone can take advantage of non-mobile powered wireless routers to implement more sophisticated and resource-demanding transmission techniques than those implemented in user devices. Consequently, the wireless backbone can realize a high degree of spatial reuse and wireless links covering longer distance at higher speed than conventional WLAN technologies.

Reliability. The wireless backbone provides redundant paths between each pair of endpoints, significantly increasing communications reliability, eliminating single points of failure and potential bottleneck links within the mesh. Network resilience and robustness against potential problems (e.g., node failures, and path failures due to temporary obstacles or external radio interference) is also ensured by the existence of multiple possible destinations (i.e., any of the egress points toward the wired Internet) and alternative routes to these destinations.

Self-management. The adoption of peer-to-peer networking to build a wireless distribution system provides all the advantages of ad hoc networking, such as self-configuration and self-healingness. Consequently, network setup is automatic and transparent to users. For instance, when adding additional nodes in the mesh, these nodes use their meshing functionalities to automatically discover all possible wireless routers and determine the optimal paths to the wired network. In addition, the existing wireless routers reorganize, taking into account the new available routes. Thus, the network can easily be expanded, because the network self-reconfigures to assimilate the new elements.

Off-the-Shelf Solutions for Building Mesh Networks

Among the commercial application case studies for wireless mesh networks described earlier, we omitted the independent (i.e., not owned by ISPs) community network case. Community networks are systems that allow neighbors to connect their home networks

[4] *Talks, videos, and presentations are available at http://research.microsoft.com/meshsummit*

together. The advantages of building up community networks are several. For instance, community networks could be used to provide shared cost-effective broadband Internet access to a neighborhood, to implement neighborhood surveillance and emergency response systems, and to distribute content useful to the neighborhood (e.g., a neighborhood portal providing a community with an online bulletin board that allows neighbors to post items for sale or trade gossip). Again, wireless mesh could be the technological driver to realize this vision. Nevertheless, the commercial deployment of community networks is still in its infancy. Nowadays, the majority of community network implementations are experimental and non-commercial trials funded and operated by government agencies, non-profit organizations, municipalities, and research institutions, and are based on *nonproprietary off-the-shelf* technologies. In this section we briefly sketch the design choices of one of these experimental trials, the Roofnet network,[5] because it exemplifies the typical advantages and limitations of off-the-shelf solutions for building wireless mesh networks.

Roofnet is an experimental and independent multihop 802.11b mesh network consisting of about 50 houses located in Cambridge, Massachusetts, installed and operated by the Massachusetts Institute of Technology (MIT). The network participants are volunteers who accept hosting in their apartments the equipment required to implement a mesh node. One of the main objectives pursued during the design of the Roofnet network has been to employ only open source software and to maintain reasonably low costs. Consequently, IEEE 802.11 is the radio technology used in the Roofnet community, because cheap network cards operating in unlicensed bands are available. Moreover, many commercial mesh networks rely on directional antennas for increased range, but Roofnet nodes use mainly omnidirectional antennas to reduce the per-node costs. Only the gateways (i.e., the nodes bridging the mesh network with the wired Internet backbone) are equipped with directional antennas to provide extended coverage. The Roofnet user node is a computer working as a wireless router, equipped with open source software. Both wireless and wired network cards are mounted on the Roofnet node. The wireless network card is used to connect to the other mesh nodes. A multihop routing protocol optimized to find paths with links of good quality is used to route traffic within the mesh. Each Roofnet node also runs a Web server, a network address translator (NAT), and a Dynamic Host Configuration Protocol (DHCP) server on its wired Ethernet port. The DHCP server and NAT provide a dynamic host configuration for the user's other computers attached to the home wired LAN. Hence, the Roofnet node also acts as a router for the user's home network. Finally, the Web server provides a simple configuration interface (to turn DHCP on and off, and set the IP address of the wired interface) and a status monitor showing which routes are available and their current metrics.

Proprietary Solutions for Building Mesh Networks

The growing interest in wireless mesh applications has boosted industrial efforts to develop solutions to make wireless mesh networks a reality. Several companies and manufactures are now selling proprietary solutions for both indoor and outdoor environments. These solutions adopt radically different approaches and protocols, making these systems incompatible. Some vendors (e.g., Tropos, BelAir, Firetide, LocustWorld and Strix) initially focused on products based on standard IEEE 802.11 technologies, but adopting proprietary software solutions. For instance, Tropos' outdoor systems are cellular Wi-Fi networks where each Wi-Fi cell behaves as a wireless routed LAN. The company has developed its own wireless routing protocol, called Predictive Wireless Routing Protocol (PWRP), that does not rely only on hop count to detect transmission paths, but compares packet error rates and other network conditions to determine the best path at a given moment. BelAir, Firetide, Tropos, and Strix also have 802.11 products for indoor environments, but they adopt radically different solutions. Firetide, Tropos, and Strix, for instance sell indoor mesh networks. In Firetide's and Tropos' products, their outdoor and indoor access points provide the same functionalities and are differentiated mainly in hardware capabilities (e.g., antenna technologies, power requirements). BelAir's solutions provide indoor coverage from outdoors by deploying outdoor devices within line of sight or near line of sight of a building, which generate radio signals that penetrate building windows to illuminate the interior. A special case is the LocustWorld company that produces mesh routers, called MeshBoxes, based on open source software components. Specifically, the core LocustWorld MeshAP device, which adopts as its routing algorithm a Linux-based implementation of the AODV protocol (a public domain protocol developed by the IETF MANET Working Group), is available for download from the LocustWorld Website as an open product. On the other hand, commercial projects are required to pay for fully assembled mesh access points, hardware components, and customized functionalities.

Several other vendors like Radiant and MeshNetwork are manufacturing solutions based on proprietary radio technologies. The motivation behind this design choice is that the 802.11 technology has been developed to provide very high data rates over short distances to stationary computers using a very low-cost low-power radio. Consequently, the 802.11 radio technology is not optimized to support mobile and wide-range applications. For this reason, the MeshNetwork company has developed a proprietary radio platform, called quadrature-division multiple access (QDMA™), that includes capabilities such as multitap rake receivers (commonly found in cell phones) and real-time equalization algorithms to compensate for the rapidly varying RF conditions typically encountered in real-world mobile environments. The MeshNetwork company has also developed a proprietary hybrid ad hoc routing protocol that combines both proactive and reac-

Roofnet is an experimental and independent multi-hop 802.11b mesh network consisting of about 50 houses located in Cambridge, MA. Participants are volunteers who agreed to host in their apartments the equipment required to implement a mesh node.

[5] *http://www.pdos.lcs.mit.edu/roofnet/*

The IEEE 802.15 project is devoted to the definition of PHY and MAC specifications for establishing short-range wireless connectivity for small groups of fixed, portable and moving computing devices.

tive routing algorithms, called MeshNetworks Scalable Routing (MSR™). MeshNetworks' radio technology still operates in the industrial, scientific, and medical (ISM) unlicensed band (2.4 GHz). Other vendors like Radiant Networks have developed proprietary radio technologies working in licensed bands in the 26–28 GHz range.

OPEN STANDARDS IMPLEMENTING WIRELESS MESH NETWORKING TECHNIQUES

Open standard radio technologies are essential for industry because they enable economies of scale, which bring down the cost of equipment and ensure interoperability. For this reason several IEEE standard groups are actively working to define specifications for wireless mesh networking techniques. These standardization activities differ in the network types they target. In particular, special task groups have been established to define the requirements for mesh networking in wireless personal area networks (WPANs), WLANs, and wireless metropolitan area networks (WMANs). Although at different degrees of maturity, the following emerging standards may be identified: IEEE 802.11s, IEEE 802.15.5, IEEE 802.16a, and IEEE 802.20. This section is not meant to provide a detailed description of these proposed specifications, but to shed light on the different efforts currently ongoing to implement mesh networking features in future wireless technologies.[6]

IEEE 802.15.5

The IEEE 802.15 project is devoted to the definition of PHY and MAC specifications for establishing short-range wireless connectivity for small groups of fixed, portable, and moving computing devices, such as PCs, PDAs, peripherals, cell phones, pagers, and consumer electronics. In November 2003 the IEEE P802.15.5 Mesh Network Task Group was formed to determine the necessary mechanisms that must be present in the PHY and MAC layers of WPANs to enable mesh networking. The use of mesh networking in the WPAN environment is motivated by the power limitations of mobile devices. Specifically, employing mesh-like multihopping communications increases the coverage of WPANs and allows shorter links to be used, providing both higher throughputs and fewer retransmissions. Indeed, meshing capabilities are particularly important when using ultra wideband (UWB) communications, because the bandwidth of UWB wireless links decreases very rapidly (the indoor channel rolls off as the third power of distance). In this case, using shorter links significantly increases the throughput. However, the challenge is to integrate the mesh networking paradigm into 802.15-like MAC protocols. In particular, the 802.15.1 MAC adopts a cluster-based network architecture, where devices are grouped in small *piconets*, each with a piconet controller. Moreover, considering the limited resources available in these digital devices, a lightweight implementation of mesh networking techniques should be devised.

IEEE 802.11S

The IEEE 802.11 Working Group is an umbrella that contains several standards committees developing technologies for the WLAN environment. The efforts of the standardization activities currently underway promise to lead in the near future to the availability of highly interoperable 802.11-based standards providing higher speeds (more than 100 Mb/s), quality of service (QoS) support, faster handoffs, and several additional capabilities. Relevant to the mesh networking paradigm is the extension under development by the P802.11s ESS Mesh Networking Task Group. The scope of this TG is to extend the IEEE 802.11 architecture and protocol for providing the functionality of an extended service set (ESS) mesh (i.e., access points capable of establishing wireless links among each other to enable automatic topology learning and dynamic path configuration). The idea behind this proposed amendment is to extend the IEEE 802.11 MAC protocol to create an IEEE 802.11 wireless distribution system that supports both broadcast/multicast and unicast delivery at the MAC layer using radio-aware metrics over self-configuring multihop topologies. The 802.11s TG is expected to start discussing proposals for the standard specification in the second quarter of 2005; however, the release of the completed standard is not expected before the end of 2006.

IEEE 802.16A

In 1999 the 802.16 Working Group was established to address the "first-mile/last-mile" connection in WMANs, working toward local multipoint distribution system (LMDS)-type architectures for broadband wireless access. The WMAN network, as specified in the 802.16 standard [4], employs a point-to-multipoint (PMP) architecture where each base station (BS) serves a number of subscriber stations (SSs) in a particular area. A PMP system is a star-shaped network where each subscriber connects to the same central hub. The BS transmits on a broadcast channel to all the SSs, while the SSs have point-to-point links with the BS. At the high frequencies (> 10 GHz) used in 802.16 systems, line-of-sight (LOS) communications are needed because the system can tolerate a limited amount of multipath interference. The need for reliable non-LOS (NLOS) operations, together with the opportunity to expand the system scope to license-exempt bands, has led to the development of the IEEE 802.16a standard. The adoption of NLOS operations allowed 802.16a standard mesh extensions to be included in the standard. It is useful to consider how the time-division multiple access (TDMA)-based MAC layer of a 802.16a system supports this optional mesh mode. In mesh mode all SSs may have direct links with other SSs, and the data traffic can be routed through other SSs and occur directly between SSs. Communications in the direct links can be controlled by either a centralized or distributed algorithm. In centralized scheduling, the BS determines the flow assignment from the resource requests of the SSs. Subsequently, the SSs determine the actual schedule for their neighbors (i.e., the SSs to which they have direct links) from these flow assignments by using a common

[6] *Draft standards and public documentation can be downloaded from the IEEE 802 Standards Committee Web site (http://www.ieee802.org/)*

algorithm. In distributed scheduling, all the nodes including the BS shall coordinate their transmissions in their two-hop neighborhood and broadcast their schedules (available resources, requests, and grants) to all their neighbors. Although the definitive standards have already been released, commercial products compliant with them are just appearing on the market. For this reason, the WiMAX forum has been established, which is working to facilitate the deployment of broadband wireless networks based on the 802.16 suite of standards by promoting and ensuring the interoperability of manufactured equipments (similar to what the Wi-Fi Alliance did to promote the IEEE 802.11 standard for WLANs).

IEEE 802.20

Recently, several IEEE working groups have turned their attention to mobile broadband. In December 2002 the establishment of IEEE 802.20, the Mobile Broadband Wireless Access (MBWA) Working Group, was approved. 802.20 systems are intended to provide ubiquitous mobile broadband wireless access in a cellular architecture (e.g., macro/micro/picocells), supporting the mesh networking paradigm (i.e., NLOS communications) in both indoor and outdoor scenarios. Simultaneously, the IEEE 802.16 WG, under Task Group e, is developing an amendment to the 802.16a specification to support subscriber stations moving at vehicular speeds, conceiving a system for combined fixed and mobile broadband wireless access. Despite the fact that 802.16e and 802.20 standards will both specify new mobile air interfaces for wireless and mobile broadband services, there are some important differences between them. 802.16e will add mobility in the 2–6 GHz licensed bands, while 802.20 aims for operation in licensed bands below 3.5 GHz. Moreover, 802.16e is looking at the mobile user walking around with a PDA or laptop, while 802.20 addresses high-speed mobility issues (speeds up to 250 km/h). More important, the 802.16e specification will be based on an existing standard (802.16a), while 802.20 is starting from scratch. Both working groups are still in preliminary stages, and no public specifications have been released yet. The 802.20 project plans to release a draft standard to submit for approval in the second semester of 2006.

Although the above standards target different network environments, these technologies are not complementary and overlap as far as many proposed functionalities. Consequently, network operators that want to deploy solutions for the last-mile broadband wireless Internet access can take advantage, for instance, of both emerging 802.11s and 802.11a products. Nowadays, Wi-Fi-based solutions appear advantageous because they are already established and operate in unlicensed cost-free frequency bands. Nevertheless, it is feasible to envision integration between WiMAX and Wi-Fi, particularly considering that the 802.16a MAC and PHY layers are optimized for long-distance wireless links. In Fig. 3 we show a wireless mesh that fully exploits the advantages of the WiMAX technology, implementing both wireless PMP communications between the wireless routers and the Internet backbone, and mesh-based communications among the wireless

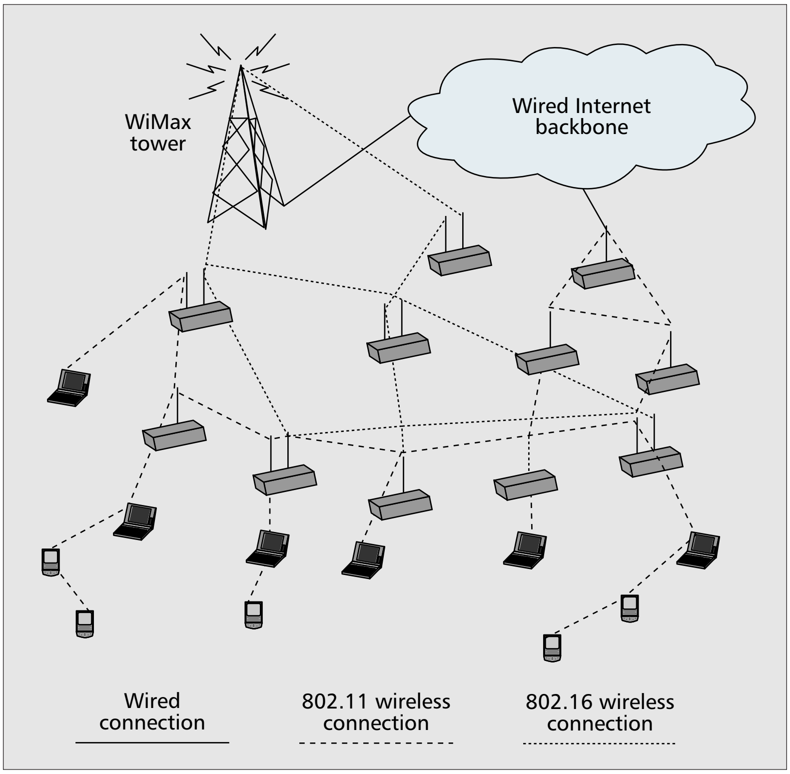

Figure 3. *Integration of WiMAX and Wi-Fi technologies in large-scale wireless mesh networks.*

routers. Once a wireless mesh network based on Wi-Fi products is installed, the integration of WiMAX will be straightforward. Indeed, 802.16 wireless links can easily be added to the existing network to either expand the network or introduce additional capacity in the wireless backbone. Consequently, WiMAX products can offer low-cost flexible alternatives for builing the wireless backbone in outdoor scenarios.

Key Research Challenges

The mesh network architecture, as conceived earlier, is an economically viable solution for the wide deployment of high-speed, scalable, and ubiquitous wireless Internet services. However, the major technical challenges of building a large-scale high-performance multihop wireless backhaul system are not solved yet. Indeed, the wireless infrastructure meshing formed through multihop communications among wireless routers and access points (Fig. 2) cannot be treated simply as a large multihop ad hoc network, because the structure and functionalities of such a network are radically different from those of a *general* ad hoc network. In practice, this simplification will undoubtedly lead to the well-known scalability limits of ad hoc networks due to the dramatic degradation of throughput and delay performance as the network diameter increases [5]. Consequently, one of the major problems to address while building a multihop wireless backhaul network is the *scalability* of both the network architecture and protocols. Hence, in the following sections we discuss the most relevant and promising research activities, focusing on the design and development of a

To cope with interference, smart antennas or adaptive array processing can be utilized to enhance both the energy efficiency and multiple access interference rejection capability of the high-throughput wireless backbone. The key idea is to exploit the beamforming capability of the transmit/receive antenna arrays.

scalable and high-performance wireless backbone for mesh networks.

HIGH-CAPACITY AND RELIABLE RADIO INTERFACES FOR THE WIRELESS BACKBONE

Currently, there are several research efforts to improve the capacity of wireless mesh networks by exploiting such alternative approaches as multiple radio interfaces, multiple-input multiple-output (MIMO) techniques, beamforming antennas, and opportunistic channel selection.[7] Multiple channels and/or radio interfaces could increase network capacity by exploiting the independent fading across different frequencies or the orthogonality of frequency bands. Similarly, systems employing multiple antennas for both transmitting and receiving (generally called MIMO systems) improve the capacity and reliability of wireless backbones by exploiting antenna diversity and spatial multiplexing. Diversity provides the receiver with several (ideally independent) replicas of the transmitted signal and is therefore a powerful technique to combat fading and interference. On the other side, spatial multiplexing divides the channel into multiple "spatial channels" through which independent data streams or signals can be coded and transmitted simultaneously. As a consequence, diversity techniques make the channel less fading, which is of fundamental importance for wireless backbones, where deep fades can occur and the channel changes slowly, causing fades to persist over a long period of time. Nevertheless, when strong interference is also present, diversity processing alone cannot improve the signal. To cope with interference, smart antennas or adaptive array processing can be utilized to enhance both the energy efficiency and multiple access interference rejection capability of the high-throughput wireless backbone. The key idea is to exploit the beamforming capability of the transmit/receive antenna arrays. Roughly speaking, beamforming creates an effective antenna pattern at the receiver with high gain in the direction of the desired signal and low gain in all other directions. Hence, the exploitation of directional transmissions could suffice to ensure a wireless backbone with high speed and a high degree of spatial reuse [6].

DESIGNING SCALABLE AND OPPORTUNISTIC NETWORKING FUNCTIONS

Although the use of multiple antennas at the wireless routers in combination with signal processing and coding is promising in providing a high-capacity wireless backhaul system, it is not enough to achieve a scalable wireless backbone. For instance, it is well known that as the number of users increases, random MAC protocols suffer from increased contention in the network. Moreover, users' traffic traversing the wireless backbone does not have a unique fixed destination, but rather can be delivered to any wired access point. In addition, several paths may exist at the same time to reach a given access point; path capacity and channel bandwidth could be highly variable. Consequently, new scalable and distributed scheduling, MAC, and routing protocols have to be designed to efficiently manage data traffic. These algorithms must be aware of the characteristics of the physical channel, which leads to the need for *cross-layer* design among physical and networking functions. Nearly all the literature focusing on cross-layering to optimize networking functions exploits *multi-user* diversity, that is, the condition when, in a system with many users, different users experience peaks in their channel quality at different time instants [7]. For instance, in this case it is proved that the scheduler should allocate transmission opportunities to users with the most favorable channel conditions [7]. The mesh network environment adds further degrees of freedom in the scheduling process, because the scheduling policies could exploit additional types of diversity such as spatial diversity (spatial channels opened by a multi-antenna wireless backbone implemented at the PHY layer) and frequency diversity (radio technologies using multiple frequency channels) to enhance throughput. Moreover, the design of scheduling policies for a multichannel, multihop, and multidestination system is extremely challenging because opportunistic selection of the high-quality channel cannot be performed locally in the single wireless router, but should be coordinated among all the wireless routers forming the backbone network. Consequently, the scheduling process in a wireless mesh network is intrinsically distributed, where the coordination among wireless routers is achieved via the exchange of messages containing information on channel conditions and traffic demands.

The MAC and PHY layers play a crucial role in providing the scalability and performance optimization required for wireless mesh networking. Furthermore, to fully exploit the potential capacity improvement ensured by the adoption of optimized transmission and antenna technologies, it is fundamental that the routing protocol discovers high-quality routes by explicitly considering the current network conditions. Most of the current routing protocols for multihop communications typically choose optimized (in the sense of minimum hop count, maximum lifetime of the route, or maximal residual power in the nodes along the route) paths without taking link quality into account. Therefore, several research efforts are devoted to the definition of novel routing metrics that correctly account for the loss rate and channel bandwidth of each link forming the path [8]. Moreover, the routing protocol for a wireless backbone needs to be redesigned not only to deal with the path diversity, but also to address the distinct nature of the wireless backbone network with respect to a general ad hoc network. In particular, the user traffic to the Internet does not need to follow the same path, but could be forwarded to any of the Internet egress points in the multihop wireless backhaul network. Consequently, the routing protocol should opportunistically select the "best wire" (i.e., the optimized path, subject to performance constraints) toward any wired access point. Finally, the routing protocol could effectively benefit from the existence of nonmobile powered wireless infrastructure to exploit hybrid ad hoc routing that combines both proactive and reactive techniques. In the wireless backbone formed by stationary wireless routers, it is reasonable to envi-

[7] *See, for example, the presentations held at the Microsoft Mesh Networking Summit 2004 at http://research.microsoft.com/meshsummit)*

sion that a link-state routing protocol analogous to a traditional wired routing protocol such as Open Shortest Path First (OSPF) could be used. Recently, a scalable link state routing protocol has been designed that minimizes the cost of maintaining a consistent view of the network, called Hazy Sighted Link State (HSLS) routing [9]. An open source implementation of the HSLS protocol is under development by the CUWiN project.

Finally, it is worth pointing out that mesh networking, as a special case of ad hoc networking, should fully implement self-management, self-configuration, and self-healing features in all layers of the network architecture. Consequently, a key research challenge is also to ensure that the scalable and opportunistic networking functions designed specifically for the mesh networks effectively fulfill the requirements of the peer-to-peer networking paradigm adopted in the wireless backbone.

SYSTEM-WIDE RESOURCE MANAGEMENT

The wireless backbone forming the core of a mesh network provides a backhaul communication service. End users' traffic is transparently routed to and from the wired Internet employing a multihop wireless path traversing the wireless backbone. It is an essential requirement for the backhaul network to ensure that all users in the network achieve a *fair* share of system resources. Unfortunately, current networking protocols are not appropriate for multihop wireless backbone networks, usually inducing severe unfairness and scarce performance to users located far from the available Internet egress points. Hence, a coordinated multihop resource management algorithm must be developed to achieve high performance while preserving a system-wide notion of fairness [2]. Fairness in ad hoc networks has been extensively studied in the last years. However, the distinct structure of the wireless backbone requires that a new fairness model be defined to address the distinct objectives and characteristics of such a network. In particular, both max-min and proportional per-flow fairness are inadequate fairness objectives in multihop wireless backhaul networks, because wireless routers must manage aggregated traffic flows traversing the network. In [10] a novel fairness model has been proposed that addresses the requirements of multihop aggregated flows, aimed at eliminating the spatial bias by ensuring that each user receives the same fair share of resources independent of how far it is from the Internet entry point (i.e., independent of its spatial location).

Coordinated resource management is required not only to tackle the issue of providing system-wide fairness and to exploit spatial reuse in the wireless backbone, but also to provide a prompt reaction to variations in system capacity due to changes in traffic patterns, channel conditions, and contention. Considering the intrinsic large-scale nature of the wireless backbone, to achieve system-wide performance objectives the resource management algorithm must be distributed. However, careful design of network control has to be employed to trade off the additional overhead of increased protocol information required to perform more precise control and the benefits derived by opportunistic exploitation of this information. Consequently, analysis of system capacity and scalability should incorporate the impact of protocol overheads and operations.

A coordinated resource management is required not only to tackle the issue of providing system-wide fairness and to exploit the spatial reuse in the wireless backbone, but also to provide a prompt reaction to the variations in system capacity due to changes in traffic patterns, channel conditions and contention.

ACKNOWLEDGMENTS

This work was partially funded by the Italian Ministry for Education and Scientific Research (MIUR) in the framework of the FIRB-VICOM project, by the CREANET-NET Research Consortium under the NewInternet project, and by the Information Society Technologies program of the European Commission under the IST-2001-38113 MobileMAN project.

REFERENCES

[1] I. Chlamtac, M. Conti, and J.J.–N. Liu, "Mobile Ad Hoc Networking: Imperatives and Challenges," *Ad Hoc Networks*, vol. 1, no. 1, July 2003, pp. 13–64.

[2] R. Karrer, A. Sabharwal, and E. Knightly, "Enabling Large–Scale Wireless Broadband: The Case for TAPs," *ACM SIGCOMM Comp. Commun. Rev.*, vol. 34, no. 1, Jan. 2004, pp. 27–34.

[3] E. Baccarelli *et al.*, "Broadband Wireless Access Networks: a Roadmap on Emerging Trends and Standards," *Broadband Services: Business Models and Technologies for Community Networks*, I. Chlamtac, A. Gumaste, and C. Szabo, Eds., Wiley, Mar. 2005.

[4] C. Eklund *et al.*, "IEEE Standard 802.16: A Technical Overview of the WirelessMAN™ Air Interface for Broadband Wireless Access," *IEEE Commun. Mag.*, vol. 40, no. 6, June 2002, pp. 98–107.

[5] P. Gupta and P. R. Kumar, "The Capacity of Wireless Networks," *IEEE Trans. Info. Theory*, vol. 46, no. 2, Mar. 2000, pp. 388–404.

[6] H. Bölcskei *et al.*, "Fixed Broadband Wireless Access: State of the Art, Challenges, and Future Directions," *IEEE Commun. Mag.*, vol. 39, no. 1, Jan. 2001, pp. 100–108.

[7] X. Quin, R. Berry, "Exploiting Multiuser Diversity for Medium Access Control in Wireless Networks," *Proc. IEEE INFOCOM 2003*, San Francisco, CA, 30 Mar.–3 Apr. 2003, vol. 2, pp. 1084–94.

[8] R. Draves, J. Padhye, and B. Zill, "Routing in Multi–Radio, Multi–Hop Wireless Mesh Networks," *Proc. ACM MobiCom '04*, Philadelphia, PA, Sept. 26–Oct. 1, 2004, pp. 114–128.

[9] C.A. Santivanez *et al.*, "On the Scalability of Ad Hoc Routing Protocols," *Proc. IEEE INFOCOM 2002*, New York, NY, June 23–27, 2002, vol. 3, pp. 1688–97.

[10] V. Gambiroza, B. Sadeghi, and E. Knightly, "End–to–End Performance and Fairness in Multihop Wireless Backhaul Networks," *Proc. MobiCom '04*, Philadelphia, PA, Sept. 26–Oct. 1, 2004, pp. 287–301.

BIOGRAPHIES

RAFFAELE BRUNO (raffaele.bruno@iit.cnr.it) received a Laurea degree in telecommunications engineering in 1999 and a Ph.D. degree in computer engineering in 2002, both from the University of Pisa, Italy. He is currently a junior researcher at the Italian National Research Council. His research interests are in the area of wireless and mobile networks with emphasis on MAC protocols for ad hoc networks and wireless LANs.

MARCO CONTI (marco.conti@iit.cnr.it) is a senior researcher at IIT-CNR. He co-authored the book *Metropolitan Area Networks* (Springer, 1997) and is co-editor of the book *Mobile Ad Hoc Networking* (IEEE-Wiley, 2004). He has published more than 150 research papers. He has served as TPC chair of the IFIP-TC6 conferences Networking 2002, PWC 2003, and WONS 2004. He is currently TPC co-chair of the IEEE Symposium WoWMoM 2005. He is Associate Editor of *Pervasive and Mobile Computing* (Elsevier).

ENRICO GREGORI is currently a research director with the Italian National Research Council. He has authored more than 100 papers in the area of computer networks. He was General Chair of the IFIP TC6 conferences Networking 2002 and PWC 2003. He is on the editorial boards of the journals *Cluster Computiing* and *Computer Networks*. His current research interests include ad hoc networks, sensor networks, wireless LANs, and the evolution of TCP/IP protocols.