

PART I

GENERAL ISSUES

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MULTIHOP AD HOC NETWORKING: THE EVOLUTIONARY PATH

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ABSTRACT

In this chapter we discuss the evolution of the mobile/multihop ad hoc networking paradigm. This paradigm has often been identified with the technologies developed inside the MANET IETF working group. For this reason we first review the failures and the success stories in the MANET research. Specifically, we analyze the reasons why the MANET paradigm does not have a major impact on computer communications. Then, starting from the lessons learned from the MANET research activities, we discuss how the multihop ad hoc networking paradigm has evolved toward a set of pragmatic networking approaches that are currently penetrating the mass market. Specifically, in this chapter we discuss four successful networking paradigms that emerged from the evolution of the multihop ad hoc networking concept: mesh, opportunistic, vehicular, and sensor networks. In these cases the multihop ad hoc paradigm is applied in a pragmatic way to extend the Internet and/or to support well-defined application requirements, thus providing a set of technologies that have a major impact on the wireless-networking field.

1.1 INTRODUCTION

At the end of the 1990s, the proliferation of mobile computing and communication devices (e.g., cell phones, laptops, handheld digital devices, personal digital

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assistants, or wearable computers) fueled the explosive growth of the mobile computing market and cellular networks, and WiFi hot spots quickly replaced wired access networks. While infrastructure-based networks offer a great way for mobile devices to get network services, it takes time and potentially high cost to set up the necessary infrastructure everywhere. These costs and delays may not be acceptable for dynamic environments where people and/or vehicles need to be temporarily interconnected in areas without a preexisting communication infrastructure (e.g., intervehicular and disaster networks), or where the infrastructure cost is not justified (e.g., in-building networks, residential communities networks, etc.). In these cases, infrastructureless networks, often referred to as ad hoc networks or self-organizing networks, provide a more efficient solution [1,2]. Single-hop ad hoc networks are the simplest form of self-organizing networks obtained by interconnecting devices that are within the same transmission range. Several wireless-network standards support the single-hop ad hoc network paradigm: IEEE 802.15.4 for short-range low data rate (< 250 kbps) networks (also known as Zigbee), Bluetooth (IEEE 802.15.1) for personal area networks, and the 802.11 standards' family for high-speed LAN ad hoc networks (see Chapter 2 in this book). Nearby nodes can thus communicate directly by exploiting wireless-network technologies in ad hoc mode. In a multihop network, often referred to as Mobile Ad hoc Networks (MANETs), the network nodes (e.g., the users' mobile devices) must cooperatively provide the functionalities usually provided by the network infrastructure (e.g., routers, switches, servers). In a MANET, users' devices with wireless interface(s) (typically 802.11 in ad hoc mode) activate communication sessions with the other mobile devices to perform data transfer operations without the need of any network infrastructure. The potentialities of this networking paradigm made ad hoc networking an attractive option for building 4G wireless networks, and hence MANET immediately gained momentum and this produced tremendous research efforts in the mobile-network community (see, for example, references 1 and 2). However, in spite of the enormous research efforts, after more than 15 years of intense research activities, the MANET technology has only a marginal role in the wireless networking field: It is applied only in very specialized scenarios. Indeed, as pointed out in reference 3, while from an academic standpoint MANET has been a very productive research area, the impact of this networking paradigm on civilian computer communications has been negligible. More precisely, while MANET research produced an extensive literature that highly influenced the development of the next generation of multihop ad hoc networks, from a usage standpoint MANET research has been a failure. This is mainly due to a lack of realism in the research approach/objectives that produced tons of scientific papers but only a very limited number of real deployments, with limited involvement of real users and no killer application. However, by exploiting the lessons learned in the MANET research, along with the scientific results produced, the scientific community has been able to turn the multihop ad hoc networking paradigm in a successful networking paradigm by applying it in several classes of networks that are currently penetrating the mass market. As discussed in this chapter, relevant examples of these technologies include mesh, opportunistic, vehicular, and sensor networks.

In this chapter we discuss the evolution of the multihop ad hoc networking paradigm. Specifically, Section 1.2 is devoted to analyze and discuss the MANET research by first presenting the main scientific achievements in this research area (with a special attention to the highly innovative *cross-layering* concept) and then discussing the lessons learned from MANET “failure.” Then, in Section 1.3 we review the most successful networking paradigms based on the multihop ad hoc networking, by discussing the results already achieved and the open challenges. Section 1.4 concludes the chapter.

1.2 MANET RESEARCH: MAJOR ACHIEVEMENTS AND LESSONS LEARNED

In this section we review the scientific results in MANET research and then we discuss the reasons why this paradigm does not have a major impact on the wireless-networking field, and we conclude with a set of lesson learned from MANET research.

1.2.1 Major Achievements in MANET Research

The MANET research focused on what we call *pure general-purpose* MANET, where *pure* indicates that no infrastructure is assumed to implement the network functions and no authority is in charge of managing and controlling the network. *General-purpose* denotes that these networks are not designed with any specific application in mind, but rather to support any legacy TCP/IP application. Specifically, the researchers concentrated their efforts to design and evaluate algorithms and protocols to implement efficient communications in a scenario like the one shown in Figure 1.1. Here, users’ devices cooperatively provide the functionalities that are usually provided by the network infrastructure (e.g., routers, switches, servers). In this way, mobile nodes

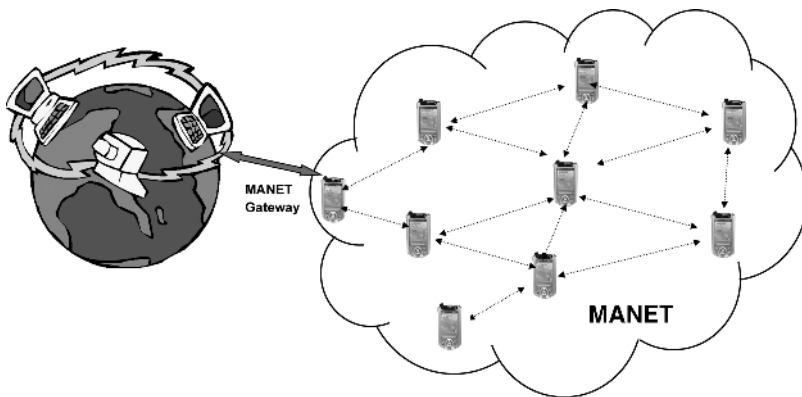


Figure 1.1 MANET topology.

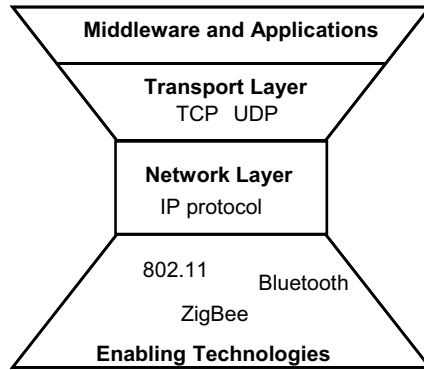


Figure 1.2 MANET layered stack.

not only can communicate with each other, but also can access Internet by exploiting the services offered by MANET gateway nodes, thus effectively extending Internet services to the non-infrastructure area (e.g., see references 4 and 5).

Pure general-purpose MANET represents a major departure from the traditional computer-network paradigms calling for a complete redesign of the network architecture and protocols. This has generated intense research activities. An in-depth overview of MANET research activities can be found in reference 2, while reference 1 summarizes the main results and challenges in MANET research.

The MANET IETF working group has been the reference point for the research activities on pure general-purpose MANET. The MANET IETF WG adopted an IP-centric view of a MANET (see Figure 1.2) that inherited the TCP/IP protocols stack layering with the aim of redesigning the network protocol stack to respond to the new characteristics, complexities, and design constraints of MANET [6]. All layers of the protocol stack were the subjects of intensive research activities. Hereafter, according to a layered view of the protocol stack (see Figure 1.2), we will briefly summarize the main research directions/results, from the enabling technologies up to middleware and applications.

1.2.1.1 Enabling Technologies. Enabling technologies are the basic block of MANET that guarantees direct single-hop communications between users' devices. Therefore, intense research activities focused on investigating the suitability of existing wireless-network standards to support multihop ad hoc networks with special attention to the IEEE 802.11 family (e.g., see references 7–10), to Bluetooth (e.g., see references 7, 11, and 12), and, more recently, to ZigBee (e.g., see references 13 and 14). Typically, these wireless network standards have not been designed for supporting multihop ad hoc networks; hence several enhancements, both at the MAC and physical layer have been proposed and evaluated for improving these technologies when operating in ad hoc mode. Enhancements at the physical layer include the use of directional antennas and power control [15], the use of OFDM, improved signal processing schemes, software defined radio, and MIMO technologies; while

at the MAC layer there have been several proposals for controlling the collisions and interferences among nodes still guaranteeing an efficient energy consumption [1]. An updated analysis of the enabling technologies for multihop ad hoc networks is presented in Chapter 2 of this book.

1.2.1.2 Networking Layer. MANET research efforts mainly focused on the networking layer, with a special attention to routing and forwarding, because these are the basic networking services for constructing a multihop ad hoc network. Routing is the function of identifying the path between the sender and the receiver, and forwarding, the subsequent function of delivering the packets along this path. These functions are strongly coupled with the characteristic of the network topology. Due to the unpredictable and dynamic nature of MANET topology, legacy routing protocols developed for wired networks are not suitable for multihop ad hoc networks, and this stimulated an intense research activity that produced an impressive (and continuously increasing) number of routing protocol proposals (see reference 16 for an updated list). Routing and forwarding protocols can be classified according to the cast property—that is, whether they use a *Unicast*, *Geocast*, *Multicast*, or *Broadcast* forwarding. Broadcast is the basic mode of operation over a wireless channel; each message transmitted on a wireless channel is generally received by all neighbours located within one hop from the sender. The simplest implementation of the broadcast operation to all network nodes is by flooding, but this may cause the *broadcast storm problem* due to redundant re-broadcast [17]. Schemes have been proposed to alleviate this problem by reducing redundant broadcasting. A discussion on efficient broadcasting schemes is presented in reference 18. Multicast routing protocols come into play when a node needs to send the same message, or stream of data, to a subset of the network-node destinations. Geocast forwarding is a special case of multicast that is used to deliver data packets to a group of nodes situated inside a specified geographical area. From an implementation standpoint, geocasting is a form of “restricted” broadcasting: Messages are delivered to all the nodes that are inside a given region. This can be achieved by routing the packets from the source to a node inside the geocasting region and then applying a broadcast transmission inside the region. Position-based or location-aware routing algorithms, by providing an efficient solution for forwarding packets toward a geographical position, constitute the basis for constructing geocasting delivery services [19]. Location-aware routing protocols use the nodes’ position (i.e., geographical coordinates) for data forwarding. A node selects the next hop for packets’ forwarding by using the physical position of its neighbors, along with the physical position of the destination node: Packets are sent toward the known geographical coordinates of the destination node [20].

Unicast forwarding means a one-to-one communication; that is, one source transmits data packets to a single destination. It is the basic forwarding mechanism in computer networks; for this reason, unicast routing protocols comprise the largest class of MANET routing protocols. According to the MANET WG, unicast routing protocols are classified into two main categories: *proactive routing protocols* and *reactive (on-demand) routing protocols*. Proactive routing protocols are derived from legacy Internet distance-vector and link-state protocols. They attempt to

maintain consistent and updated routing information for every pair of network nodes by propagating, proactively, route updates at fixed time intervals. Conversely, reactive routing protocols establish the route to a destination only when requested (the source node usually initiates the route discovery process by sending a route request message). Once a route has been established, it is maintained until either the destination becomes inaccessible or until the route is no longer used. In particular, three main routing protocols emerged from the MANET field and constitute a reference for other multihop ad hoc networks: two reactive routing protocols, AODV (and its successor DYMO) and DSR, and one proactive protocol, OLSR. A survey on MANET routing protocols is presented in reference 21, while reference 1 summarizes the main research directions in this area.

In addition to proactive and reactive protocols, other classes of protocols have been identified to improve the network performance at least in specific scenarios. *Hybrid protocols* combine both proactive and reactive approaches, thus trying to bring together the advantages of both. *Energy-aware routing protocols* take into consideration the energy available in the network nodes to select the path(s) for data forwarding. This may imply either (a) to minimize the energy consumed to forward a packet from the source to the destination or (b) to maximize the network lifetime by preserving as much as possible the network connectivity. *Hierarchical routing* aims at reducing the overhead by structuring the network on more levels and allowing the multihop communications among only few nodes, representing a group of nodes at a lower level. Cluster-based routing is a relevant example of hierarchical routing. The basic idea behind clustering is to group the network nodes into a number of overlapping clusters. Paths are recorded only between clusters (instead of between nodes); this enables the aggregation of the routing information and consequently increases the routing algorithms scalability. In its original definition, inside the cluster, one node is in charge of coordinating the cluster activities (*clusterhead*). Beyond the clusterhead, inside the cluster, we have ordinary nodes that have direct access only to their clusterhead and gateways—that is, nodes that can hear two or more clusterheads and that relay the traffic among different clusters. Cluster-based routing has been extensively adopted in multihop ad hoc networks, and consequently the definition of a cluster and cluster-based routing has significantly evolved.

1.2.1.3 Higher Layers. On top of the networking protocols, MANET generally assumes the Internet transport protocols. Unfortunately, the Transmission Control Protocol (TCP) does not work properly in this scenario, as extensively discussed in the literature (see, e.g., reference 1). To improve the performance of the TCP protocol in a MANET, several proposals have been presented. Most of these proposals are modified versions of the legacy TCP protocol used in the Internet. However, TCP-based solutions might not be the best approach when operating in MANET environments, and hence several authors have proposed novel transport protocols tailored on the MANET features (e.g., see reference 22 and references therein).

Middleware and applications constitute the less investigated area in the MANET field. Indeed, general-purpose MANETs have been designed to support legacy TCP/IP applications without a clear understanding of the applications for which multihop ad

hoc networks are an opportunity and can thus represent killer applications for this network paradigm. Lack of attention to the applications probably constitutes one of the major causes for the negligible MANET impact in the wireless networking field. Lack of attention to the applications also limited the interest to develop middleware solutions tailored on MANETs. However, the similarities between MANET and peer-to-peer (p2p) systems (such as distribution and cooperation) has stimulated some research activities toward using the p2p computing model for MANET (e.g., see references 23–25 and references therein). Indeed by integrating p2p systems on top of ad hoc networks makes the variety of p2p applications and services available to MANET users, as well.

1.2.1.4 Cross-Layer Research Issues. In addition to an in-depth reanalysis of all layers of the protocol stack, MANET research also focuses on cross-layering research topics with special attention to energy efficiency [26], security [27] and cooperation [28,29]. Indeed, energy efficiency and security issues are not associated with a specific layer, but they affect the design of the whole protocol stack. Energy efficiency emerged as a key design constraint with the development of mobile devices, which rely on batteries for energy [30]. In MANET this constraint becomes a dominant one because mobile devices do not simply operate as users' devices but they must implement all the network basic functions (like routing and forwarding); hence the (simple) power-saving policies implemented in infrastructure-based networks [30,31], which put a device in a sleeping state when it has no data to transmit/receive, are not effective/sufficient in MANET. In an infrastructure wireless network, energy management strategies are local to each node and are aimed to minimize the node energy consumption [30,32]. This metric is not suitable for ad hoc networks where nodes must also cooperate to network operations to guaranteeing the network connectivity. A greedy node that remains most of the time in a sleep state, without contributing to routing and forwarding, will maximize its battery lifetime but compromise the network operations. In MANET we can therefore identify (at least) two classes of power-saving strategies: *local strategies*, which typically operate on small timescales (say milliseconds), and *global strategies* that operate on longer timescales. Local strategies operate inside a node, and try to put the network interface in a power-saving mode with a minimum impact on transmit and receive operations. These policies, which have been inherited by the mobile computing research, typically operate at the physical and MAC layer, with the aim of maximizing the node battery lifetime without affecting the protocols of the higher layers [30]. On the other hand, MANET research extensively investigated global strategies aimed to maximize the network lifetime through policies that try to put in a power-saving state the maximum number of network nodes without compromising the network coverage. The research activities in this field, which we can refer to as topology control, have been one of the most prolific MANET research areas [33]. The topology control research includes the control of the transmitting node power because it affects both the amount of energy drained from the battery for each transmission, and the number of feasible links (i.e., the network topology). A reduced transmission power allows spatial reuse of frequencies—which can help increasing the total throughput and minimizing the interference—but increases the number of

hops toward the destination. On the other hand, by increasing the transmission power, we increase the per-packet transmission cost (negative effect), but we decrease the number of hops to reach the destination (positive effect) because more and longer links become available. Finding the balance is not a simple undertaking. Another important part of the literature related to energy efficiency in ad hoc networks concentrated on energy efficient routing where the transmitting power level is an additional variable in the routing protocol design [26].

Security and Cooperation is the other key cross-layer challenge in multihop networks. The self-organizing environment introduces new security issues that are not addressed by the legacy security services provided for infrastructure-based networks. Indeed, in addition to typical challenges of wireless environments such as vulnerability of channels and nodes, the absence of infrastructure, along with dynamically changing topologies, makes MANET security a challenging task, both at the network (e.g., secure routing to cope with malicious nodes that can disrupt the correct functioning of a routing protocol by modifying routing information and/or generating false routing information) and enabling technologies level (e.g., cryptographic mechanisms implemented to prevent unauthorized accesses) [27]. However, in MANET, security mechanisms that solely enforce the correctness or integrity of network operations are not sufficient. Indeed a basic requirement for keeping the network operational is to enforce the contribution of each node to the network operations, despite the conflicting tendency of nodes toward selfishness (e.g., motivated by the energy scarcity) [34]. Therefore, a self-organizing network must be based on an incentive for users to collaborate, thus avoiding selfish behaviors (see reference 29). Several solutions, proposed in the MANET literature, present a similar approach to the cooperation problem: They aim at detecting and isolating misbehaving nodes through a mechanism based on a watchdog and a reputation system. Another class of approaches is based on introducing an economic model to enforce cooperation. Specifically, these works assume the introduction of a virtual currency, which is used by the network nodes to request services from the other nodes. When a node wants to send a packet, it has to use the virtual currency to pay for the transmission. On the other hand, a node gets a virtual currency reward when it forwards a packet for the benefit of other nodes. Cooperation among nodes is the results of a balancing between conflicting self-interests, and therefore game theory models have been extensively used to evaluate MANET cooperation algorithms.

1.2.1.5 Cross-Layer Architectures. The IETF MANET WG proposes a view of mobile ad hoc networks as an evolution of the Internet [6]. This mainly implies an IP-centric view of the network, along with the use of a layered architecture (see Figure 1.2). The use of the IP protocol has two main advantages: It simplifies MANET interconnection to the Internet, and it guarantees the independence from wireless technologies.

The layered paradigm has greatly simplified the design of computer networks and has led to a robust and scalable Internet architecture. However, results show that in wireless networks, where several resources are scarce (e.g., energy and bandwidth), the layered approach is not equally valid in terms of performance [35]. Indeed, with

the layered approach, each layer in the protocol stack is designed and optimized independently from the other layers, and this leads to a suboptimal utilization of the network resources. This might be critical in a resource-constrained environment such as multihop ad hoc networks. Furthermore, in MANET some functions cannot be assigned to a single layer. For example, as discussed above, energy management, security, and cooperation cannot be completely implemented inside a single layer, but they are implemented by combining and exploiting mechanisms implemented in several layers, and this requires a joint design of these layers to take advantage of their interdependencies [36]. For example, from the energy management standpoint, power control and multiple antennas at the link layer are coupled with scheduling at the MAC layer, as well as with energy-constrained and delay-constrained routing at network layer. This clearly indicates that significant performance gains can thus be expected by moving away from a strict layered approach in designing the MANET protocol stack. On the other hand, the layered approach guarantees a flexible network architecture, and supporters of this approach point out that cross-layer optimizations may compromise the modular design of the protocol stack (which has been a major element in the success of the TCP/IP architecture); this can introduce severe problems [37]:

- As a consequence of cross-layer optimizations, protocols may become tightly coupled, and a change in a protocol propagates to the others.
- Combining several cross-layer optimizations together may cause mutual interferences among the layers, which may result in a “spaghetti” protocol-stack design, making architectural maintenance a challenging task.

Therefore the main issue is to find a balance between performance optimization and the flexibility of the protocol stack. The main question is to what extent the pure-layered approach needs to be modified. At one extreme we have solutions based on *layer triggers*. Specifically, *layer triggers* are predefined signals to notify some events to the higher layers (e.g., failure in data delivery), which thus increase the cooperation among layers still preserving the principle of separation among layers. A full cross-layer design represents the other extreme, which optimizes the overall network performance by exploiting layers’ interdependencies at the maximum extent. For example, the physical layer can adapt rate, power, and coding to meet the requirements of the application given current channel and network conditions; the MAC layer can adapt its behavior to underlying-link interference conditions as well as to the delay constraints and priorities of higher layers. Adaptive routing protocols can be developed based on current link, network, and traffic conditions and requirements. Finally, the middleware can utilize a notion of soft quality of service (QoS), which adapts to the underlying network conditions to deliver the highest possible QoS to the applications [35].

The wide spectrum of possible alternatives to exploit MANET cross-layering for improving the network performance has generated a large body of literature. Different criteria can be used to classify the existing cross-layer approaches (e.g., see reference 38). Hereafter, we classify the cross-layering approaches into four main categories:

- *Interlayer Communications.* Some communication channels are established among protocols belonging to different layers. Typically, a layered organization of the architecture is preserved, but new interfaces are defined to enable communications among not adjacent layers.
- *Interlayer Tuning.* The protocols at different layers are implemented in an independent way, but their parameters are jointly optimized to increase the overall system performance. In the simplest case the protocol tuning is performed offline before the network start up. In this case the legacy-layered architecture is fully preserved. The other extreme in this set of solutions is represented by online joint tuning of the protocol parameters. In this case the layered architecture is modified by the insertion of control loops among protocols belonging to different layers.
- *Interlayer Design.* A joint design of two (or more) protocols belonging to different layers destroys the architecture modularity, because layers' independence is not preserved. When a protocol is modified/replaced also, all the other protocols of the stack, whose designs depend on the modified protocol, need to be modified/replaced.
- *Unlayered Design.* In this case the layered organization is not used and novel organizations are used to process and forward the packets traveling through the network nodes. The Haggie architecture is a mature example of this approach [39].

The above categories cover the whole spectrum of solutions, from layered architectures enhanced with layer triggers to unlayered architectures. Indeed, in the first three cases a layered organization of the architecture is maintained, but layers' independence and the architecture modularity are not always guaranteed. Generally, interlayer communications still preserve the architecture modularity, while interlayer design destroys the modularity by exploiting a joint design of layers. Interlayer tuning is intermediate between interlayer communications and interlayer design. Last, in the unlayered approach the layer concept disappears.

While several proposals exist for introducing cross-layer optimization in mobile ad hoc networks, most of these works only focus on showing the performance gain possible by introducing cross-layering among two to three layers of the protocol stack, and they do not take care of how cross-layer interactions can be effectively introduced in the network architecture. Only a limited number of works exist that have defined a full cross-layer architecture; among these, only in few cases an implementation of the cross-layer architecture have been provided, while the remaining proposals have been only validated by simulation.

The MobileMAN architecture [36] is one of the few (and probably the first) types of cross-layer architecture for ad hoc networking that has been tested and evaluated not only via simulation but also implemented in a real prototype through which extensive measurements of its performance have been carried out [25].

Figure 1.3 shows the MobileMAN cross-layer architecture. In this architecture, cross-layer interactions are implemented through data sharing. Indeed, as shown in Figure 1.3, the key element of the architecture is a shared memory, "Network status"

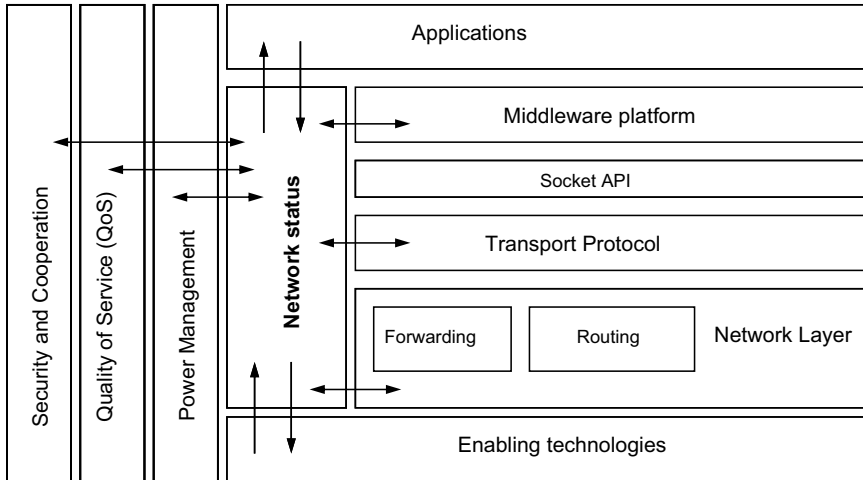


Figure 1.3 The MobileMAN architecture.

in the figure, which is a repository of all the network status information collected by the network protocols—for example, protocol-parameter values and state variables. All protocols can access this memory to write the information to share them with the other protocols and (b) read information produced/collected by the other protocols. This avoids duplicating the layers’ efforts for collecting network-status information, thus leading to a more efficient system design. In addition, interlayer cooperations can be easily implemented by shared variables. Each protocol is still completely implemented inside one layer, as in full-layered architectures [40]. Therefore, the MobileMAN cross-layer approach can be classified among the interlayer communication solutions; it uses a shared memory for implementing interlayer communications, which guarantees a high level of independence among layers.

The MobileMAN approach to cross-layering, based on information sharing among layers, has been adopted by successive architectures: WIDENS [41], GRACE [42], CrossTalk [43], ÉCLAIR [44], and XIAN [45]. The main difference among these architectures is in the way information sharing is implemented and the type of cross-layer optimizations. Specifically, while WIDENS, CrossTalk, and XIAN implement cross-layer interactions by (mainly) exploiting interlayer communications, in GRACE and ÉCLAIR the parameters of several protocols are jointly optimized (i.e., interlayer tuning). Table 1.1 provides a comparison in terms of efficiency and flexibility of the various cross-layer architectures. We exploited the contents of Table 1 in reference 43 to fill the complexity/overhead and the flexibility rows of Table 1.1.

Results presented in Table 1.1 show that the MobileMAN approach presents the lowest complexity and the highest flexibility, making the MobileMAN solution one of the most promising directions for introducing cross-layer interactions in a mobile ad hoc architecture still maintaining the basic principles (layers’ separation and modularity) of legacy layered architectures.

Table 1.1 Comparison of Cross-Layer Architectures

Parameter	MobileMAN	WIDENS	GRACE	CrossTalk	ECLAIR	XIAN
Interlayering	Interlayer communication	Interlayer communication	Interlayer tuning	Interlayer communication	Interlayer tuning	Interlayer communication
Protocol optimization	Local	Local	Global and local	Local (networkwide)	Global	Locals
Network stack adaptation	Local	Local	Global	Local and global	Global	Local
Added complexity and overhead	Low	Low	High	High	High	Low
Flexibility	High	Low	Low	High	Low	Low

1.2.2 Problems and Lessons Learned from MANET Research

From a research standpoint, MANET research produced several important results (as summarized in Section 1.2.1), but in terms of real-world implementations and industrial deployments, the pure general-purpose MANET paradigm suffers from scarce exploitation and low interest among the users. An extensive discussion about the major problems in the MANET research is presented in reference 3, where it is pointed out that MANET research generally lacks of “realism” both from the technical and socioeconomic perspective.

The MANET research was mainly driven by military-research challenges while its usage for supporting civilian applications was left in the background. Indeed the pure general-purpose MANET scenario is very suitable for battlefield scenarios where a completely infrastructureless communication paradigm—based on the cooperation among a large number of nodes to relay the traffic through several intermediate hops by adopting specialized communication hardware—is meaningful and valuable. On the other hand, this scenario seems too ambitious for civilian applications where “limited” off-the-shelf wireless-network technologies are used, and the cooperation among nodes cannot be assumed a priori. No attempt was done to customize the military-driven scenario to realistic civilian scenarios; the academia has simply taken the pure general-purpose MANET as the relevant scenario (also for civilian networking) and has tried to address all the relevant research challenges associated to this scenario. Moreover, the MANET research has been characterized by the continuous emergence of new research challenges (e.g., security and cooperation, energy management, transport protocols) addressing relevant theoretical problems, while the exploitation plans for this technology have been left in the background. On the other hand, to successfully bootstrap a technology like MANET (based on users’ cooperation), it is fundamental to build up a community of users by providing MANET prototypes with simple but effective communication services (e.g., file sharing and messaging), through which the users can experience the features of this technology with the aim to test the user acceptance and possibly identify the application scenarios where this networking paradigm can have an added value. In this initial stage, advanced networking features (e.g., energy-saving and/or cooperation and security mechanisms) do not contribute to a better user experience; instead they make the system design more complex and hence unstable (due to an increased error probability during its implementation), thus negatively affecting the users’ experience. To summarize, a major weakness in MANET research has been the lack of *implementation, integration, and experimentation* [46]. Except for a few attempts in the Uppsala University APE testbed,¹ the Dartmouth College Experimental testbed,² and the MobileMAN project,³ all research efforts concentrated on solving very interesting theoretical problems for pure general-purpose MANET and testing the proposed solution only via simulation. In addition, MANET simulation studies generally lack

¹<http://apetestbed.sourceforge.net/>

²<http://www.cs.dartmouth.edu/research/node170.html>

³<http://cnd.iit.cnr.it/mobileMAN>

of accuracy, and this further reduced the credibility of MANET research. Indeed, as extensively discussed in reference 3 and the references therein, while the use of simulation techniques in the performance evaluation of communication networks is a consolidated research area, most MANET simulation studies did not correctly apply the established methodologies. Problems have been pointed out in all aspects of a simulation study, from the simulation models (e.g., the mobility models, the characterization of the wireless-communication channels, etc.) to the model solution (e.g., transient vs. steady-state simulation, simulation tools, etc.) up to the analysis of the simulation output. The lack of accuracy, in one or more of the above points, has drastically reduced the credibility of MANET research.

MANET research is also weak from a socioeconomic standpoint, even if the socioeconomic dimension was included in the initial design [47]. Generally, the use of the MANET paradigm is motivated by the possibility to build a network when no infrastructure exists, or to have a “free” network where the users can communicate without any cost provided that the node density is enough. However, the few reports available on MANET perception from the users’ perspective (see, e.g., the MobileMAN project deliverables⁴) indicate that the potential MANET users have huge difficulties in seeing how ad hoc networks can help them in the everyday life. The possibility of a communication service with no charge is not enough to compensate the lack of reliability in the communications and the additional difficulties in using this type of network. Furthermore, the users remarked the need to use this technology to better understand its potentialities, while (as said before) there has been a lack of MANET deployments that can be used by not-expert users. Last, ICT-expert users (i.e., computer science Ph.D. students) that had the opportunity to directly test the MANET technology were not able to indicate scenarios in which they can clearly benefit from a pure general-purpose MANET. Indeed, the most interesting applications of the multihop ad hoc technology they indicated are close to the definition of a mesh network.

1.3 MULTIHOP AD HOC NETWORKS: FROM THEORY TO REALITY

In the previous sections we have reviewed the MANET research, pointing out that, while from a research standpoint some important results have been achieved, pure general-purpose MANET has scarce penetration in the wireless market. In this section we show that by learning from the MANET lessons, and by exploiting the MANET theoretical results in realistic networking scenarios, the scientific community has been able to design a set of novel multihop ad hoc networking paradigms that are currently penetrating the mass market. Specifically, as discussed in reference 48 to turn MANETs into a commodity, we have to move to more pragmatic approaches where some of the following conditions apply:

⁴<http://cnd.iit.cnr.it/mobileMAN/pub-deliv.html>

- The multihop ad hoc networking paradigm is extended to include some infrastructure elements (e.g., mesh routers) to provide a cost-effective wireless broadband extension of the Internet. The *mesh networks* constitute the most relevant example of this approach.
- The nodes mobility is not considered as a problem to mask (to support the legacy TCP/IP protocol stack) but as an opportunity to exploit by designing a completely new networking paradigm. The *opportunistic networks* constitute the most relevant example of this approach.
- The multihop ad hoc networking paradigm is applied to specialized fields where the self-organizing nature of this paradigm and the absence of a pre-deployed infrastructure are a plus and not a limitation. Notable examples of this approach are application-driven networks such as, *vehicular networks* and *sensor networks*.

In the next sections we will briefly discuss these emerging multihop ad hoc networking paradigms that will be analyzed in depth in the next chapters of the book.

1.3.1 Mesh Networks

The mesh-network paradigm is a meaningful example of how we can turn the pure and general-purpose MANET paradigm (and the related research results) in a pragmatic networking approach that has immediately gained the users and market acceptance. Specifically, the key mesh-network enablers are (i) a well-defined set of application scenarios to drive/motivate its design (i.e., providing a flexible and “low cost” extension of the Internet) and (ii) a reduction of the MANET complexities with the introduction of a (fixed) backbone, which limits the impact of node mobility to the last hop, provides a routing infrastructure that does not require users’ cooperation, relaxes the energy constraints in the protocols design, and so on [49].

The research on *wireless mesh networks* (WMNs), as opposed to that on MANET, has been focused from the beginnings on implementation, integration, and experimentation, to test the WMN solutions on real networks with real users. In the beginning, WMNs have been mainly developed as a result of the initiative of a community of users that setup IEEE 802.11 wireless links among their houses to establish a community mesh network (see Figure 1.4) supporting applications such as file sharing or VoIP, or sharing an high-speed Internet access. WMN is now a consolidated technology for a low cost extension of the Internet with few-hop wireless links, mainly using the WiFi technology (see Figure 1.5). Metropolitan-scale WMNs are now a reality in many modern urban areas supported by municipalities and government organizations [50]. Indeed, solutions have been developed to set up robust WMN backbones (e.g., see references 51 and 52) and to reliably forward the users data both inside the WMN and to/from the Internet (e.g., see references 53 and 54). However, several aspects of this technology are still under intensive investigations to make this technology more robust and able to support more advanced services.

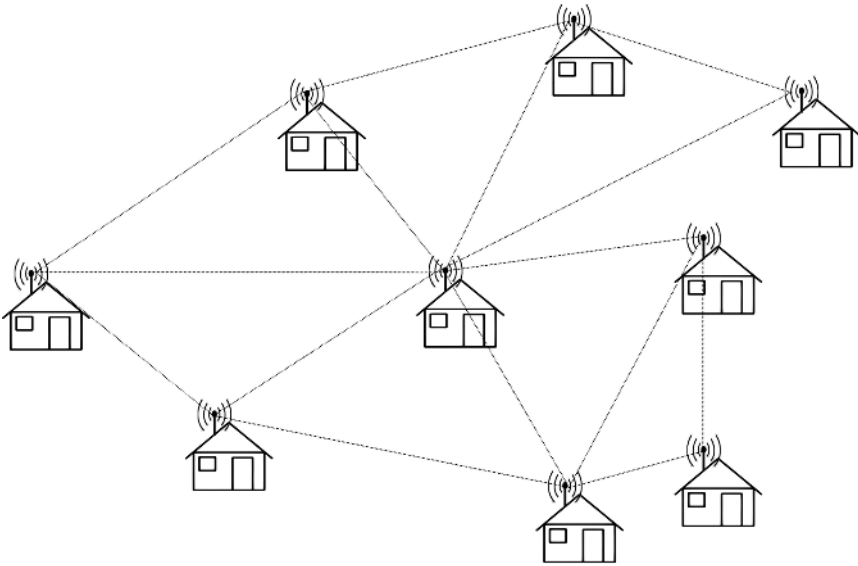


Figure 1.4 Community mesh networking.

Open research issues include novel routing paradigms [55], QoS support [56–58], security [59], and experimental versus simulation studies [60]. Two chapters of this book are dedicated to some hot research topics in the WMN field. Specifically, Chapter 7 presents and discusses the use of multiradio and multichannel solutions to increase

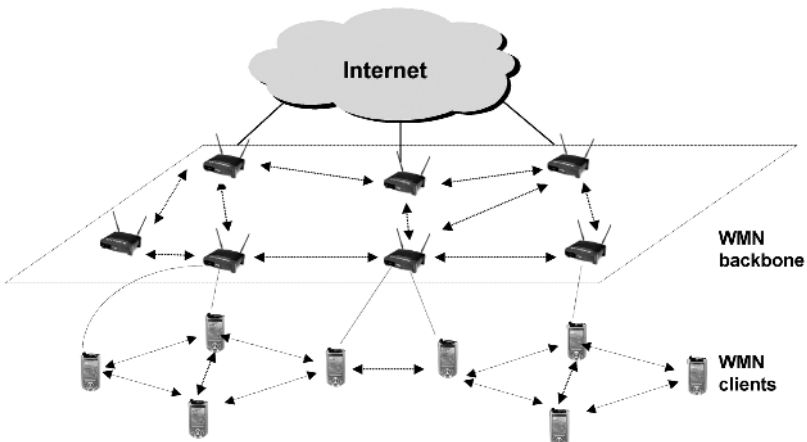


Figure 1.5 Wireless mesh networking organization.

the capacity of WMNs, while Chapter 8 focuses on providing QoS guarantees in WMNs.

1.3.2 Opportunistic Networks

The opportunistic networking paradigm is one of the most innovative generalisations of the MANET paradigm. Indeed, while MANET represents an engineering approach to mask the node mobility by constructing “stable” end-to-end paths as in the wired Internet, opportunistic networks do not consider the node mobility as a problem (to mask) but as an opportunity to exploit. In opportunistic networks the mobility of the nodes creates contact opportunities among nodes, which can be used to connect parts of the network that are otherwise disconnected. Specifically, according to this paradigm (which is also referred to as delay tolerant or challenged networks), nodes can physically carry buffered data while they move around the network area, until they get in contact with a suitable next-hop node—that is, until a forwarding opportunity exists. In this way, when a node does not have a good next hop to forward the data, it simply stores the data locally without discarding it, as would occur in a MANET. In addition, with the opportunistic paradigm, data can be delivered between a source and a destination even if an end-to-end path between the two nodes never exists by exploiting the sequence of connectivity graphs generated by nodes’ movement (see Figure 1.6). Therefore, the opportunistic networking paradigm constitutes a generalization of the legacy Internet paradigm (where communications can occur only if an

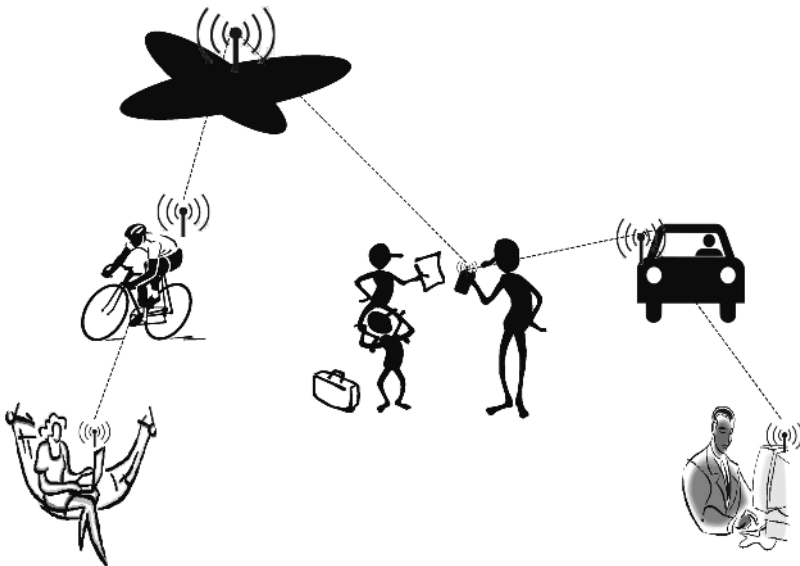


Figure 1.6 Opportunistic networking.

end-to-end path exists), and it seems very suitable for the communications in pervasive environments where the environment is saturated of devices (with short-range wireless technologies) that can self-organize in a network for local interactions among users. In these scenarios, the network will be generally partitioned in disconnected islands, which might be interconnected by exploiting the nodes' mobility.

Opportunistic networking is an area of growing interest with several challenging research issues. The dynamic and often unpredictable nature of the network topology makes the routing in opportunistic networks one of the most compelling challenges. This has already generated intense research activities in the area, which has produced several proposals for routing and forwarding in opportunistic networks [61,62]. Currently, the research interests focus on routing protocols (such as *Bubble Rap* [63], *HiBOP* [64], *Propicman* [65], and *SimBet* [66]) that try to exploit the nodes' social context for optimized routing.

While routing in opportunistic networks is a well-investigated area, other areas, such as data dissemination and security and privacy, still need more intense research activities. Data dissemination is a natural follow-up of the research on routing and forwarding algorithms. One of the most interesting use cases for opportunistic networks is indeed the sharing of content available on mobile users' devices. For these reasons, content dissemination is now a hot research area where some interesting results can be found in references 67–69.

Privacy is currently one of the main concerns in opportunistic networks as the context information exchanged among nodes (for selecting the best forwarder) might include sensible information. Very promising results to tackle the problem are presented in reference 70. Security is a hot and key challenge for opportunistic networks, as mobile users operate on the move in open, possibly adversary, environments. A preliminary discussion on encryption, and robustness against denial of service attacks to the operations of opportunistic protocols can be found in reference 39. Another network security issue is related to preventing uncontrolled resource hogs (i.e., individuals whose message generation rate is much higher than the average), which may significantly reduce the network performance [71].

Inside the opportunistic-network field it is worth remembering the research activities carried out inside the *Delay-Tolerant Networking Research Group* (DTNRG). DTNRG is an IRTF research group,⁵ which is developing architecture and protocols to extend the Internet protocol stack in order to cope with frequent partitions, which may destroy the behavior of legacy Internet protocols (e.g., TCP). To this end, DTNRG has developed an overlay, named *Bundle Layer Protocol*, that it is implemented in some network nodes (named DTN nodes) which, during the disconnection phases, use a persistent storage to store the packets to be forwarded [72]. The bundle layer is implemented above the transport and below applications and it is aimed to mask the network disconnections to the higher layers. Instead of “small” packets, the bundle layer uses for the data transfer “long” data units called “bundles.” An overview of DTN research activities is presented in reference 73.

⁵<http://www.dtnrg.org>

An opportunistic network exploits the devices' mobility for its operations. Because humans typically carry the devices, it is the human mobility that generates the communication opportunities. Therefore, understanding and modeling the properties of the human mobility is an important research area for opportunistic networking. Studying human mobility traces is the starting point to understand the properties of the human mobility. The aim is to provide a characterization of the temporal properties of devices/humans mobility with special attention to the contact time (i.e., the distribution of the contact duration between two devices) and the inter-contact time (ICT) (i.e., the distribution of the time between two consecutive contacts between devices). The characterization of the ICT distribution has generated a great debate in the scientific community where different research groups have claimed completely different results ranging from heavy-tailed distribution functions—with [74] or without [75] an exponential cutoff—to an exponential distribution [76]. In reference 77, the authors have shown a fundamental result that helps to explain the differences among the ICT distributions claimed by different research groups. Specifically, in that paper the authors derive the conditions under which, by starting from exponential inter-contact times among individual couple of nodes, we can obtain a heavy-tailed aggregate ICT distribution (i.e., the ICT distribution between any couple of nodes). Understanding the properties of the ICT distribution is a critical issue because this distribution controls the effectiveness of several routing protocols for opportunistic networks. For example, in reference 75 the authors have shown that for a simple forwarding scheme, like the Two-Hop scheme, the expected delay for message forwarding might be infinite, depending on the properties of the ICT distribution. These results have been generalized in reference 78.

Using real-world traces is essential for the performance evaluation of opportunistic networking solutions. In fact, only with such traces the social relationships among users can be properly taken into account for the analysis of inter-user contact information. For example, in reference 79, the authors performed a social data mining experiment showing that the similarities in the user profile and the context information contained therein boost the contact probability.

Starting from the observed properties of the human mobility, several models have been proposed to provide a synthetic characterization of the human mobility to be used in the performance evaluation studies used for comparing and contrasting the mechanisms and protocols developed for opportunistic networks. Some mobility models, in addition to the inter-contact properties, also represent the impact of social relationships in the human mobility [80,81]. An updated survey on human mobility models is presented in reference 82.

Modeling and performance evaluation is currently one of the most active research areas in the study of opportunistic networks. Examples of ongoing works include the modeling of (social-aware) routing protocols in heterogeneous settings [83,84], context-based routing schemes that consider both the spatial and the temporal dimensions of the activity of mobile nodes to predict the mobility patterns of nodes [85] new theoretical models for investigating the properties of the connectivity graphs that characterize the connectivity properties of an opportunistic network [86].

Opportunistic networking is currently a very active research area, and therefore several chapters of this book are dedicated to present and discuss various aspects of the opportunistic network research: the application scenarios (Chapters 9 and 13), the mobility models (Chapter 8), opportunistic routing (Chapter 11), and data dissemination (Chapter 12).

1.3.3 Vehicular Ad Hoc NETWORKS (VANETs)

Vehicular Ad hoc NETWORKS (VANETs) are another notable example of a successful networking paradigm that is emerging as a specialization of (pure) MANETs. VANET research is well motivated by the socioeconomic value of the transportation sector, which motivates the development of advanced Intelligent Transportation System (ITS) aimed at reducing the traffic congestions, the number of traffic road accidents, and so on. Advanced ITS systems require both vehicle-to-roadside (V2R) and vehicle-to-vehicle (V2V) communications. In V2R communications a vehicle typically exploits infrastructure-based wireless technologies, such as cellular networks, WiMAX and WiFi, to communicate with a roadside base station/access point.

VANETs are based on the multihop ad hoc network paradigm. Specifically, according to this paradigm (see Figure 1.7), the vehicles on the road dynamically self-organize in a VANET by exploiting their wireless communication interfaces (e.g., 802.11p; see Chapter 2 in this book).

The V2V research field inherited MANET results related to multihop ad hoc routing/forwarding protocols [87], which have been tuned and modified for adapting them to the peculiar features of the vehicular field [88]. Special attention has been reserved for the development of optimized broadcasting protocols because several applications developed for vehicular ad hoc networks use broadcast communication services [89,90]. However, the high level of vehicles' mobility and the possibility of sparse networking scenarios (which occur when the traffic intensity is low) make inefficient the legacy store-and-forward communication paradigm used in MANET, and they push toward the adoption of the more flexible and robust store-carry-and-forward paradigm adopted by the opportunistic networks (see Section 1.3.2). The opportunistic paradigm applied to vehicular networks has recently generated a large body of literature mainly on routing protocols and data dissemination in vehicular

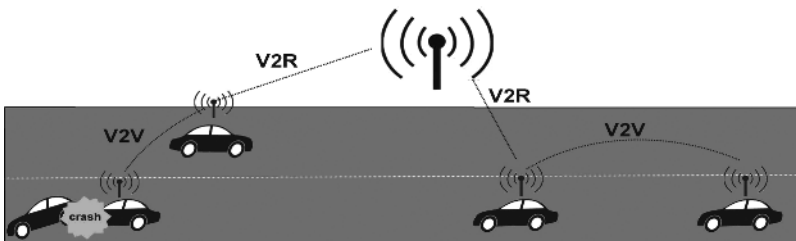


Figure 1.7 VANET.

networks (e.g., references 91 and 92). However, there are still several interesting and challenging issues to be addressed (e.g., privacy [93]); a special attention should be reserved to develop realistic models to characterize the mobility of the VANET nodes [94] and to analytically study the VANET performance [95].

V2R and V2V communication systems can support a large plethora of applications including safety applications (e.g., collision avoidance, road obstacle warning, safety message disseminations, etc.), traffic information, and infotainment services (e.g., games, multimedia streaming, etc.). An extensive survey of the vehicular applications is presented in reference 96.

Several chapters in this book are devoted to analyze the hottest research challenges in the VANET research. Chapter 14 presents a taxonomy of data communication protocols for VANET. Chapters 15 and 16 discuss VANET simulation and experimentation, respectively. Chapters 17 and 18 focus on VANET protocols and technology by presenting the MAC protocols and the use of the Cognitive radio technology for building a VANET. Chapter 19 discusses the evolution from VANET to vehicular clouds.

1.3.4 Sensor Networks

Sensor and actuator networks have a major role toward the cyber/physical world convergence. Indeed, the information about the physical reality, collected through sensor nodes, is elaborated in the cyber world to tune cyber applications and services to the physical context, and possibly modify/adapt the physical world itself through actuators [97]. Wireless sensor networks (with [98] or without actuators [99]) have therefore a major role in controlling/connecting the physical world from/to the cyber world [97]. Wireless Sensor Networks (WSNs) represent a “special” class of multihop ad hoc networks that are developed to control and monitor events and phenomena. To this end, a number of sensor nodes (with a wireless interface) are deployed inside the monitoring area. If the sensor network is sufficiently dense to guarantee a connected network, the information collected by the sensor nodes is delivered, by following the multihop paradigm through the other sensor nodes, to a sink node and through it to the Internet. If the sensor-node density is low, and hence the sensor network is disconnected, mobile elements (also referred to as data mules or message ferries) are used to collect the sensed data and deliver them to the sink [100]. Indeed the design of these networks highly depend on the application scenarios and the requirements of the applications in terms of reliability, timeliness, and so on. WSNs are successful both in the academy and industry, because they are developed for addressing specific application requirements. Thus, in the last ten years they triggered intensive scientific activities, which have produced a large body of literature to address several WSN research challenges: energy efficiency [101], MAC protocols [102], routing protocols [103], clustering algorithms [104], time [105] and clock [106] synchronization, security [107–109] coverage and connectivity [110,111], networks with mobile nodes [100], and so on. The existing literature leaves a very limited space for producing additional original scientific works on legacy WSN problems like routing, clustering, MAC protocols, synchronization, coverage, and so on. On the other hand, further research is still expected to address (i) problems ranging from QoS to privacy,

security and trust [112–117], (ii) network topology and transmission ([118,119]), (iii) realistic simulation and experiments ([120–122]), (v) specialized network scenarios [123,124], and (vi) the usage of sensor networks in challenging environments like underwater [125,126] underground [127], industrial environments [13], and so on. This book covers some of these advanced WSN research topics, including underwater sensor networks (Chapters 22 and 23), wireless sensor and robot networks (Chapter 21), and WSN with energy harvesting nodes (Chapter 20).

In the near future, a very promising research area in the sensor network field is related to the new challenges emerging from the use of mobile phones as a human-centric sensing tool [128,129]. Specifically, we can think to exploit the billions of users' mobile devices/phones as location-aware data collection instruments for real-world observations. In this way we can sense the physical world without deploying our own sensor network. This novel paradigm is known as *participatory sensing* when people take an active role into the decision stages of the sensing system [130]. A participatory system design focuses on tools that assist people to share, publish, search, interpret, and verify information collected using a custodian device [131]. On the other hand, in *opportunistic sensing* the custodian may not be aware of active applications; in this case the sensing activities are performed by the (opportunistic) exploitation of all the sensing devices available in the environment whenever there is a match with the application requirements. Indeed in a convergent physical-cyber world, a wide variety of smart devices spread in the physical world (such as RFID Tags, Sensors and Actuators, Sensor-rich Smart Phones, or Proximity Sensing Technologies) are leading to the emergence of a very dense ICT infrastructure for monitoring the physical world and collecting information about the user behaviors and requirements. In particular, multimodal sensors spread in the environment can be opportunistically exploited to infer precise information about the social behavior of the users and the social environment around them. Indeed, participatory and opportunistic sensing offers un-precedent opportunities for *pervasive urban sensing* [132]: to effectively *collect* and *process* the digital footprints generated by humans when interacting with the surrounding physical world and with the social activities therein. A major goal of these sensing activities is to investigate the *hybrid city* (i.e., a city that operates simultaneously in the cyber/digital and physical realms) and to investigate the human behavior and its socioeconomic relationships [133]. This is a highly challenging and innovative research objective that can lead to the development of novel urban applications that benefit citizens, urban planners, and policy makers. Preserving the privacy of the individuals contributing their sensed data is a major challenge for progressing toward the pervasive urban sensing [134,135].

Architectural solutions for mobile phone sensing systems still remain the subject of open research [128]. The (exclusive) local execution of computationally intensive tasks is necessarily a suboptimal approach. At the opposite end, cloud computing offers high-end resources at a nonnegligible energy cost. Opportunistic computing [39,136] may offer the best of both worlds [137]. Specifically, as indicated in Figure 1.8, individual devices may combine and exploit each other resources to boost their computing power and overcome the limitations of their own resources, without the communication energy footprint and the extreme centralization of cloud computing.

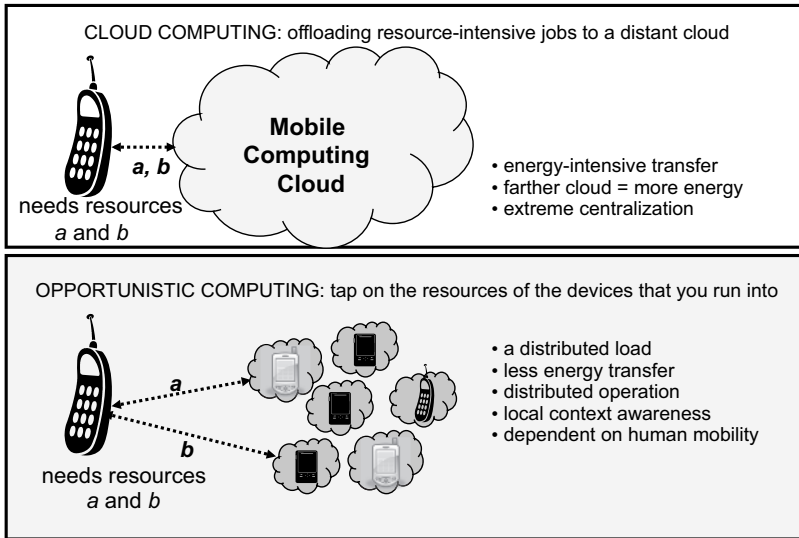


Figure 1.8 Cloud computing versus opportunistic computing in mobile phone sensing.

1.4 SUMMARY AND CONCLUSIONS

In this chapter we have discussed the evolution of the multihop ad hoc networking paradigm from both a research and usage perspective. Specifically, we started from the MANET paradigm—which was identified for many years with the multihop ad hoc networking paradigm—and we reviewed the important body of scientific literature produced in this field, and that was extensively investigated in reference 2. Special attention has been reserved for the cross-layer concept that, originally investigated in the MANET field, is now a widespread concept in the networking literature. We have concluded this analysis of the MANET literature, pointing out that the MANET paradigm does not have a significant impact on the wireless networking market due to several weaknesses in its original design. In particular, we have remarked that a major cause in the MANET failure has been the lack of realism in the design of pure large-scale and general-purpose multihop ad hoc networks. In addition, the lack of credibility in MANET simulation studies and the lack of implementation, integration, and experimentation have further limited the impact of the MANET paradigm. However, as discussed in this chapter, the lessons learned from MANET research have driven toward a pragmatic evolution of the multihop ad hoc networking concept that has generated new network technologies that have a transformative effect on the wireless networking field. These novel technologies, which include mesh, opportunistic, vehicular, and sensor networks, have generated several new research challenges that are currently generating extensive research activities. Therefore, while in reference 2 we presented an in-depth analysis of the MANET architecture and protocols, the next

chapters of this book are dedicated to the research challenges associated with these novel multihop ad hoc network technologies.

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