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Mobile ad hoc networking: imperatives and challenges

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Abstract

Mobile ad hoc networks (MANETs) represent complex distributed systems that comprise wireless mobile nodes that 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 pre-existing communication infrastructure, e.g., disaster recovery environments. Ad hoc networking concept is not a new one, having been around in various forms for over 20 years. Traditionally, tactical networks have been the only communication networking application that followed the ad hoc paradigm. Recently, the introduction of new technologies such as the Bluetooth, IEEE 802.11 and Hyperlan are helping enable eventual commercial MANET deployments outside the military domain. These recent evolutions have been generating a renewed and growing interest in the research and development of MANET. This paper attempts to provide a comprehensive overview of this dynamic field. It first explains the important role that mobile ad hoc networks play in the evolution of future wireless technologies. Then, it reviews the latest research activities in these areas, including a summary of MANET's characteristics, capabilities, applications, and design constraints. The paper concludes by presenting a set of challenges and problems requiring further research in the future.

Keywords: MAC; Routing; Energy saving; Security; Performance evaluation

1. Introduction

The proliferation of mobile computing and communication devices (e.g., cell phones, laptops, handheld digital devices, personal digital assistants, or wearable computers) is driving a revolutionary change in our information society. We are moving from the Personal Computer age (i.e., a one computing device per person) to the Ubiquitous Computing age in which a user utilizes, at the same time, several electronic platforms through which he can access all the required information whenever and wherever needed [268]. The nature of ubiquitous devices makes wireless networks the easiest solution for their interconnection and, as a consequence, the wireless arena has been experiencing exponential growth in the past decade. Mobile users can use their cellular phone to check e-mail, browse internet; travelers with portable computers can surf the internet from airports, railway stations, Starbucks and other public locations; tourists can use Global Positioning System

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(GPS) terminals installed inside rental cars to locate driving maps and tourist attractions, researchers can exchange files and other information by connecting portable computers via wireless LANs while attending conferences; at home, users can synchronize data and transfer files between portable devices and desktops.

Not only are mobile devices getting smaller, cheaper, more convenient, and more powerful, they also run more applications and network services, commonly fueling the explosive growth of mobile computing equipment market. The exploding number of Internet and laptop users driving this growth further [280]. Projections show that in the next two years the number of mobile connections and the number of shipments of mobile and Internet terminals will grow yet by another 20–50% [280]. With this trend, we can expect the total number of mobile Internet users soon to exceed that of the fixed-line Internet users.

Among all the applications and services run by mobile devices, network connections and corresponding data services are without doubt the most demanded service by the mobile users. According to a study by Cahners In-Stat Group, the number of subscribers to wireless data services will grow rapidly from 170 million worldwide in 2000 to more than 1.3 billion in 2004, and the number of wireless messages sent per month will rise dramatically from 3 billion in December 1999 to 244 billion by December 2004. Currently, most of the connections among these wireless devices are achieved via fixed infrastructure-based service provider, or private networks. For example, connections between two cell phones are setup by BSC and MSC in cellular networks; laptops are connected to Internet via wireless access points. While infrastructure-based networks provide a great way for mobile devices to get network services, it takes time and potentially high cost to set up the necessary infrastructure. There are, furthermore, situations where user required networking connections are not available in a given geographic area, and providing the needed connectivity and network services in these situations becomes a real challenge.

More recently, new alternative ways to deliver the services have been emerging. These are focused around having the mobile devices connect to each other in the transmission range through automatic configuration, setting up an ad hoc mobile network that is both flexible and powerful. In this way, not only can mobile nodes communicate with each other, but can also receive Internet services through Internet gateway node, effectively extending Internet services to the non-infrastructure area. As the wireless network continues to evolve, these ad hoc capabilities are expected to become more important, the technology solutions used to support more critical and significant future research and development efforts can be expected in industry and academy, alike.

This paper demonstrates the impetus behind mobile ad hoc networks, and presents a representative collection of technology solutions used at the different layers of the network, in particular presenting algorithms and protocols unique to the operation and dynamic configuration of mobile ad hoc networks. Mobile ad hoc network (MANET) literature is already too extensive to be covered and analyzed in detail in this article. Hereafter, we therefore present the main research areas in the MANET literature, and inside each, survey the main research directions and open issues.

Inside the ad hoc networking field, wireless sensor networks take a special role. A sensor network is composed of a large number of small sensor nodes, which are typically densely (and randomly) deployed inside the area in which a phenomenon is being monitored. Wireless ad hoc networking techniques also constitute the basis for sensor networks. However, the special constraints imposed by the unique characteristics of sensing devices, and by the application requirements, make many of the solutions designed for multi-hop wireless networks (generally) not suitable for sensor networks [12]. This places extensive literature dedicated to sensor networks beyond the scope of this paper; however, the interested reader can find an excellent and comprehensive coverage of sensor networks in a recent survey [12].

The paper is organized as follows. In Section 2, we explain why ad hoc networking is an essential component of the 4G network architectures. In Section 3, we look at mobile ad hoc networks in closer detail, covering their specific characteristics, advantages, as well as design challenges. This is followed by an analysis of MANET evolution from an historical perspective. Finally, we conclude this section by presenting the design challenges facing the MANET research community.

In Section 4, we examine ad hoc networking enabling technologies, by examining Bluetooth, and IEEE 802.11 standards in more detail. Ad hoc networking research is surveyed in Section 5, in which we focus on node location services, forwarding and routing, and TCP issues. MANET applications and middleware are discussed in Section 6. Cross-layer research areas, including, energy management, security and cooperation, Quality of Service, and performance evaluation are analyzed in Section 7. Section 8 concludes the paper.

2. 4G and ad hoc networking

A major goal toward the 4G Wireless evolution is the providing of pervasive computing environments that can seamlessly and ubiquitously support users in accomplishing their tasks, in accessing information or communicating with other users at anytime, anywhere, and from any device [268]. In this environment, computers get pushed further into background; computing power and network connectivity are embedded in virtually every device to bring computation to users, no matter where they are, or under what circumstances they work. These devices personalize themselves in our presence to find the information or software we need. The new trend is to help users in the tasks of everyday life by exploiting technologies and infrastructures hidden in the environment, without requiring any major change in the users' behavior. This new philosophy is the basis of the *Ambient Intelligence* concept [1]. The objective of ambient intelligence is the integration of digital devices and networks into the everyday environment, rendering accessible, through easy and "natural" interactions, a multitude of services and applications. Ambient intelligence places the user at the center of the information society. This view heavily relies on 4G wireless and mobile communications. 4G is all about an integrated, global network, based on an open systems approach. Integrating different types of wireless networks with wire-line backbone network seamlessly, and convergence of voice, multimedia and data traffic over a single IP-based core network are the main foci of 4G. With the availability of ultra-high bandwidth of up to 100 Mbps, multimedia services can be supported efficiently; ubiquitous computing is enabled with enhanced system mobility and portability support, and location-based services are all expected. Fig. 1 illustrates the networks and components within 4G network architecture.

Network Integration. 4G networks are touted as hybrid broadband networks that integrate different network topologies and platforms. In Fig. 1 the overlapping of different network boundaries represents the integration of different types of networks in 4G. There are two levels of integration. First is the integration of heterogeneous wireless networks with varying transmission characteristics such as Wireless LAN, WAN, PAN, as well as mobile ad hoc networks. At the second level we find the integration of wireless networks with the fixed network backbone infrastructure, the Internet, and PSTN. Much work remains to enable a seamless integration, for example that can extend IP to support mobile network devices.

All IP Networks. 4G starts with the assumption that future networks will be entirely packet-switched, using protocols evolved from those in use in today's Internet [163]. An all IP-based 4G wireless network has intrinsic advantages over its predecessors. IP is compatible with, and independent of, the actual radio access technology, this means that the core 4G network can be designed and evolves independently from access networks. Using IP-based core network also means the immediate tapping of the rich protocol suites and services already available, for example, voice and data convergence, can be supported by using readily available VoIP set of protocols such as MEGACOP, MGCP, SIP, H.323, SCTP, etc. Finally the converged all-IP wireless core networks will be packet based and support packetized voice and multimedia on top of data. This evolution is expected to greatly simplify the network and to reduce costs for maintaining separate networks, for different traffic types.

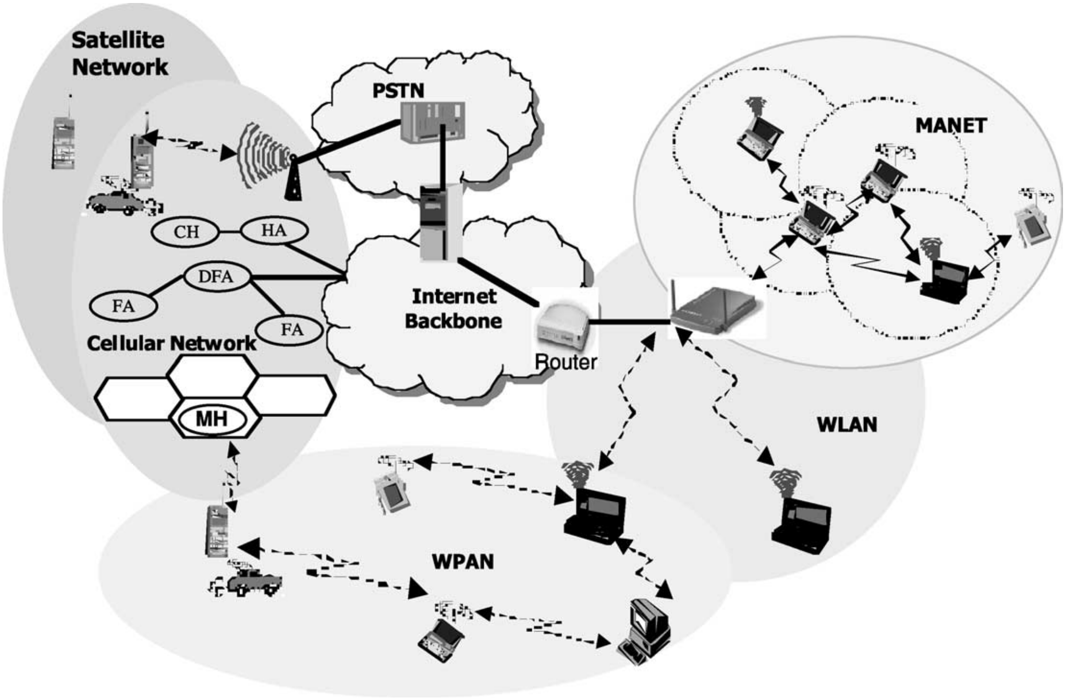

Fig. 1. 4G networks.

Lower Cost and Higher Efficiency. 4G IP-based systems will be cheaper and more efficient than 3G. Firstly, equipment costs are expected to be four to ten times lower than equivalent circuit-switched equipment for 2G and 3G wireless infrastructures. An open converged IP wireless environment further reduces costs for network build-out and maintenance. There will be no need to purchase extra spectrum as 2G/3G spectrum can be reused in 4G, and much of spectrum needed by WLAN and WPAN is public and does not require a license.

Ultra-High Speed and Multimedia Applications. 4G systems aim to provide ultra-high transmission speed of up to 100 Mbps, 50 times faster than those in 3G networks. This leap in provided bandwidth will enable high-bandwidth wireless services, allowing users to watch TV, listen to the music, browse Internet, access business programs, perform real-time video streaming and other multimedia-oriented applications, like E-Commerce, as if sitting in home or office.

Location Intelligence. To support ubiquitous computing requirements, 4G terminals need to be more intelligent in terms of user's locations and service needs, including recognizing and being adaptive to user's changing geographical positions, as well as offering location-based services [29]. Anytime anywhere requires intelligent use of location information, and the embedding of the information into various applications. Possible Location Based Services include finding nearest service providers, such as restaurant or cinema; searching for special offers within an areas; warning of traffic or weather situations; sending an advertisement to a specific area; searching for other users; active badge systems, etc. Outdoor, wireless applications can use GPS to obtain location information. GPS is a satellite-based system that can provide easy, accurate positioning information almost anywhere on earth. Many GPS implementations are available, including integrating a GPS receiver into a mobile phone (GPS/DGPS); or add fixed GPS receivers at regular intervals to obtain data to complement readings on phone (A-GPS); or by using help from fixed base stations (E-OTD). These implementations provide different fix time and accuracy ranging from 50 to 125 m. For indoor applications, since GPS signal cannot be received well inside the buildings, alternative technologies like Infrared, Ultrasound or Radio are being considered.

Non-infrastructure-based MANET are expected to become an important part of the 4G architecture. An ad hoc mobile network is a transient network formed dynamically by a collection of (arbitrarily located) wireless mobile nodes without the use of existing network infrastructure, or centralized administration. Ad hoc networks are created, for example, when a group of people come together, and use wireless communications for some computer-based collaborative activities; this is also referred to as *spontaneous networking* [93].

In a MANET, the users' mobile devices are the network, and they must cooperatively provide the functionality usually provided by the network infrastructure (e.g., routers, switches, servers). In a MANET, no infrastructure is required to enable information exchange among users' mobile devices. We can envisage these devices as an evolution of current mobile phones, and emerging PDA's equipped with wireless interfaces. The only external resource needed for their successful operation is the bandwidth, often the (unlicensed) ISM band. Nearby terminals can communicate directly by exploiting, for example, wireless LAN technologies. Devices that are not directly connected, communicate by forwarding their traffic via a sequence of intermediate devices.

MANETs are gaining momentum because they help realizing network services for mobile users in areas with no pre-existing communications infrastructure, or when the use of such infrastructure requires wireless extension [67,102]. Ad hoc nodes can also be connected to a fixed backbone network through a dedicated gateway device enabling IP networking services in the areas where Internet services are not available due to a lack of preinstalled infrastructure. All these advantages make ad hoc networking an attractive option in future wireless networks.

3. Mobile ad hoc networks

As concluded in Section 2, ad hoc networking capabilities can become essential in delivering overall next generation wireless network functionalities. Next, we will look at mobile ad hoc network applications from an historical perspective, and then we will focus on challenges in the MANET research activities.

3.1. MANET evolution

Historically, mobile ad hoc networks have primarily been used for tactical network related applications to improve battlefield communications/survivability. The dynamic nature of military operations means that military cannot rely on access to a fixed pre-placed communication infrastructure in battlefield. Pure wireless communication also has limitation in that radio signals are subject to interference and radio frequency higher than 100 MHz rarely propagate beyond line of sight (LOS) [97]. Mobile ad hoc network creates a suitable framework to address these issues by providing a multi-hop wireless network without pre-placed infrastructure and connectivity beyond LOS.

Early ad hoc networking applications can be traced back to the DARPA Packet Radio Network (PRNet) project in 1972 [97], which was primarily inspired by the efficiency of the packet switching technology, such as bandwidth sharing and store-and-forward routing, and its possible application in mobile wireless environment. PRNet features a distributed architecture consisting of network of broadcast radios with minimal central control; a combination of Aloha and CSMA channel access protocols are used to support the dynamic sharing of the broadcast radio channel. In addition, by using multi-hop store-and-forward routing techniques, the radio coverage limitation is removed, which effectively enables multi-user communication within a very large geographic area.

Survivable Radio Networks (SURAN) were developed by DARPA in 1983 to address main issues in PRNet, in the areas of network scalability, security, processing capability and energy management. The main objectives were to develop network algorithms to support a network that can scale to tens of thousands of nodes and withstand security attacks, as well as use small, low-cost, low-power radios that could support sophisticated packet radio protocols [97]. This effort results in the design of Low-cost Packet Radio (LPR) technology in 1987 [94], which features a digitally controlled DS spread-spectrum radio with an integrated Intel 8086 microprocessor-based packet switch. In addition, a family of advanced network management protocols was developed, and hierarchical network topology based on dynamic clustering is used to support network scalability. Other improvements in radio adaptability, security, and increased capacity are achieved through management of spreading keys [253].

Towards late 1980s and early 1990s, the growth of the Internet infrastructure and the microcomputer revolution made the initial packet radio network ideas more applicable and feasible [97]. To leverage the global information infrastructure into the mobile wireless environment, DoD initiated DARPA Global Mobile (GloMo) Information Systems program in 1994 [171], which aimed to support Ethernet-type multimedia connectivity any time, anywhere among wireless devices. Several networking designs were explored; for example Wireless Internet Gateways (WINGs) at UCSC deploys a flat peer-to-peer network architecture, while Multimedia Mobile Wireless Network (MMWN) project from GTE Internetworking uses a hierarchical network architecture that is based on clustering techniques.

Tactical Internet (TI) implemented by US Army at 1997 is by far the largest-scale implementation of mobile wireless multi-hop packet radio network [97]. Direct-sequence spread-spectrum, time division multiple access radio is used with data rates in the tens of kilobits per second ranges, while modified commercial Internet protocols are used for networking among nodes. It reinforces the perception that commercial wireline protocols were not good at coping with topology changes, as well as low data rate, and high bit error rate wireless links [254].

In 1999, Extending the Littoral Battle-space Advanced Concept Technology Demonstration (ELB ACTD) was another MANET deployment exploration to demonstrate the feasibility of Marine Corps war fighting concepts that require over-the-horizon (OTH) communications from ships at sea to Marines on land via an aerial relay. Approximately 20 nodes were configured for the network, Lucent's WaveLAN and VRC-99A were used to build the access and backbone network connections. The ELB ACTD was successful in demonstrating the use of aerial relays for connecting users beyond LOS. In the middle of 1990, with the definition of standards (e.g., IEEE 802.11 [131]), commercial radio technologies have begun to appear on the market, and the wireless research community became aware of the great commercial potential and advantages of mobile ad hoc networking outside the military domain. Most of the existing ad hoc networks outside the military arena have been developed in the academic environment, but recently commercially oriented solutions started to appear (see, e.g., MeshNetworks [1] and SPANworks [2]).

3.2. Ad hoc networking issues

In general, mobile ad hoc networks are formed dynamically by an autonomous system of mobile nodes that are connected via wireless links without using the existing network infrastructure or centralized administration. The nodes are free to move randomly and organize themselves arbitrarily; thus, the network's wireless topology may change rapidly and unpredictably. Such a network may operate in a standalone fashion, or may be connected to the larger Internet. Mobile ad hoc networks are infrastructure-less networks since they do not require any fixed infrastructure, such as a base station, for their operation. In general, routes between nodes in an ad hoc network may include multiple hops, and hence it is appropriate to call such networks as "multi-hop wireless ad hoc networks". Each node will be able to communicate directly with any other node that resides within its transmission range. For communicating with nodes that reside beyond this range, the node

[1] http://www.meshnetworks.com
[2] http://www.spanworks.com

needs to use intermediate nodes to relay the messages hop by hop.

The ad hoc networks flexibility and convenience do come at a price. Ad hoc wireless networks inherit the traditional problems of wireless communications and wireless networking [132]:

- the wireless medium has neither absolute, nor readily observable boundaries outside of which stations are known to be unable to receive network frames;
- the channel is unprotected from outside signals;
- the wireless medium is significantly less reliable than wired media;
- the channel has time-varying and asymmetric propagation properties;
- hidden-terminal and exposed-terminal phenomena may occur.

To these problems and complexities, the multihop nature, and the lack of fixed infrastructure add a number of characteristics, complexities, and design constraints that are specific to ad hoc networking [67,70]:

Autonomous and infrastructure-less. MANET does not depend on any established infrastructure or centralized administration. Each node operates in distributed peer-to-peer mode, acts as an independent router and generates independent data. Network management has to be distributed across different nodes, which brings added difficulty in fault detection and management.

Multi-hop routing. No default router available, every node acts as a router and forwards each others' packets to enable information sharing between mobile hosts.

Dynamically changing network topologies. In mobile ad hoc networks, because nodes can move arbitrarily, the network topology, which is typically multi-hop, can change frequently and unpredictably, resulting in route changes, frequent network partitions, and possibly packet losses.

Variation in link and node capabilities. Each node may be equipped with one or more radio interfaces that have varying transmission/receiving capabilities and operate across different frequency bands [63,64]. This heterogeneity in node radio capabilities can result in possibly asymmetric links. In addition, each mobile node might have a different software/hardware configuration, resulting in variability in processing capabilities. Designing network protocols and algorithms for this heterogeneous network can be complex, requiring dynamic adaptation to the changing conditions (power and channel conditions, traffic load/distribution variations, congestion, etc.).

Energy constrained operation. Because batteries carried by each mobile node have limited power supply, processing power is limited, which in turn limits services and applications that can be supported by each node. This becomes a bigger issue in mobile ad hoc networks because, as each node is acting as both an end system and a router at the same time, additional energy is required to forward packets from other nodes.

Network scalability. Currently, popular network management algorithms were mostly designed to work on fixed or relatively small wireless networks. Many mobile ad hoc network applications involve large networks with tens of thousands of nodes, as found for example, in sensor networks and tactical networks [97]. Scalability is critical to the successful deployment of these networks. The steps toward a large network consisting of nodes with limited resources are not straightforward, and present many challenges that are still to be solved in areas such as: addressing, routing, location management, configuration management, interoperability, security, high-capacity wireless technologies, etc.

3.3. Ad hoc networking research

The specific MANET issues and constraints described above pose significant challenges in ad hoc network design. A large body of research has been accumulated to address these specific issues, and constraints. In this paper, we describe the ongoing research activities and the challenges in some of the main research areas within the mobile ad hoc network domain. To present the huge amount of research activities on ad hoc networks in a systematic/organic way, we will use, as a reference, the simplified architecture shown in Fig. 2.

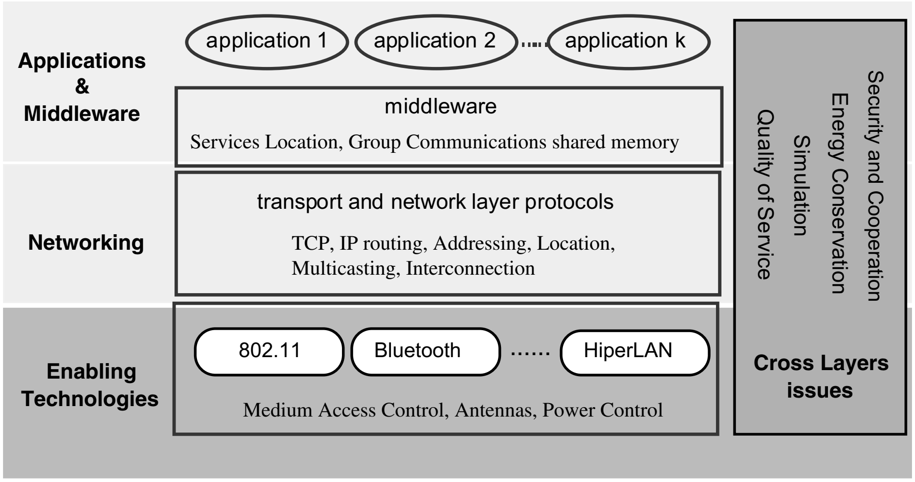

Fig. 2. A simple MANET architecture.

As shown in the figure, the research activities will be grouped, according to a layered approach into three main areas:

- Enabling technologies;
- Networking;
- Middleware and applications.

In addition, as shown in the figure, several issues (energy management, security and cooperation, quality of service, network simulation) span all areas, and we discuss them separately.

4. Enabling technologies

As shown in Fig. 3, we can classify ad hoc networks, depending on their coverage area, into several classes: Body (BAN), Personal (PAN), Local (LAN), Metropolitan (MAN) and Wide (WAN) area networks.

Wide- and Metropolitan-area ad hoc networks are mobile multi-hop wireless networks that present many challenges that are still to be solved (e.g., addressing, routing, location management, security, etc.), and their availability is not on immediate horizon. On the other hand, mobile ad hoc networks with smaller coverage can be expected to appear soon. Specifically, ad-hoc single-hop BAN, PAN and LAN wireless technologies are already common on the market [48], these technologies constituting the building blocks for constructing small, multi-hop, ad hoc networks that extend their range over multiple radio hops [67]. For these reasons, BAN, PAN and LAN technologies constitute the *Enabling technologies* for ad hoc networking. A detailed discussion of Body, Personal, and Local Ad hoc Wireless Net-

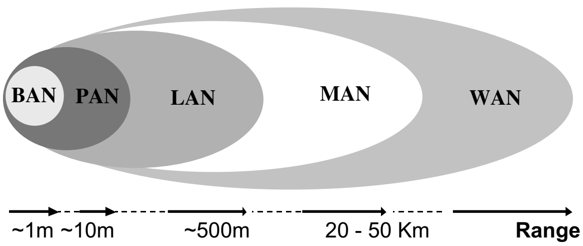

Fig. 3. Ad hoc networks taxonomy.

works can be found in [48]. Hereafter, the characteristics of these networks, and the technologies available to implement them, are summarized.

A body area network is strongly correlated with wearable computers. A wearable computer distributes on the body its components (e.g., head-mounted displays, microphones, earphones, etc.), and the BAN provides the connectivity among these devices. The communicating range of a BAN corresponds to the human body range, i.e., 1–2 m. As wiring a body is generally cumbersome, wireless technologies constitute the best solution for interconnecting wearable devices.

Personal area networks connect mobile devices carried by users to other mobile and stationary devices. While a BAN is devoted to the interconnection of one-person wearable devices, a PAN is a network in the environment around the persons. A PAN communicating range is typically up to 10 m, thus enabling the interconnection of the BANs of persons close to each other, and the interconnection of a BAN with the environment around it.

The most promising radios for widespread PAN deployment are in the 2.4 GHz ISM band. Spread spectrum is typically employed to reduce interference and bandwidth re-use.

Wireless LANs (*WLANs*) have a communication range typical of a single building, or a cluster of buildings, i.e., 100–500 m. A WLAN should satisfy the same requirements typical of any LAN, including high capacity, full connectivity among attached stations, and broadcast capability. However, to meet these objectives, WLANs need to be designed to face some issues specific to the wireless environment, like security on the air, power consumption, mobility, and bandwidth limitation of the air interface [235].

Two different approaches can be followed in the implementation of a WLAN: an *infrastructure-based* approach, or an *ad hoc networking* one [235]. An infrastructure-based architecture imposes the existence of a centralized controller for each cell, often referred to as *Access Point*. The Access Point (AP) is normally connected to the wired network, thus providing the Internet access to mobile devices. In contrast, an ad hoc network is a peer-to-peer network formed by a set of stations within the range of each other, which dynamically configure themselves to set up a temporary network. In the ad hoc configuration, no fixed controller is required, but a controller may be dynamically elected among the stations participating in the communication.

The success of a network technology is connected to the development of networking products at a competitive price. A major factor in achieving this goal is the availability of appropriate networking standards. Currently, two main standards are emerging for ad hoc wireless networks: the IEEE 802.11 standard for WLANs [133], and the Bluetooth specifications [3] [39] for short-range wireless communications [15,40,179].

Due to its extreme simplicity, the IEEE 802.11 standard is a good platform to implement a single-hop WLAN ad hoc network. Furthermore, multi-hop networks covering areas of several square kilometers can potentially be built by exploiting the IEEE 802.11 technology. On a smaller scale, technologies such as Bluetooth can be used to build ad hoc wireless Body, and Personal Area Networks, i.e., networks that connect devices on the person, or placed around him inside a circle with radius of 10 m.

In addition to the IEEE standards, the European Telecommunication Standard Institute (ETSI) has promoted the HiperLAN (HIgh Performance Radio Local Area Network) family of standard for WLANs [90]. Among these, the most interesting standard for WLAN is HiperLAN/2. The HiperLAN/2 technology addresses high-speed wireless network with data rates ranging from 6 to 54 Mbit/s. Infrastructure-based, and ad hoc networking configurations are both supported in HiperLAN/2. To a large degree, HiperLAN is still at the prototype level, and hence we will not consider it more in detail. More details on this technology can be found in [87].

[293] surveys the off-the-shelf technologies for constructing ad hoc networks; while [4] presents an in depth analysis of 802.11-based ad hoc networks, including performance evaluation and some of the open issues.

[3] The Bluetooth specifications are released by the Bluetooth Special Interest Group.

The ad hoc network size in terms of the number of active nodes is the other metric used to classify MANETs. As defined in [181], we can classify the scale of an ad hoc network as small-scale (i.e., 2–20 nodes), moderate-scale (i.e., 20–100 nodes), large-scale (i.e., 100+ nodes), and very large-scale (i.e., 1000+ nodes). In [107], it was shown that in an ad hoc network with n nodes the per-node throughput is bounded by $c/\sqrt{n}$, where c is a constant. Unfortunately, experimental results [104] indicate that with current technologies the per-node throughput decays as $c'/n^{1.68}$, and hence, with current technologies only small- and moderate-scale can be implemented in an efficient way.

4.1. Bluetooth

The Bluetooth technology is a de-facto standard for low-cost, short-range radio links between mobile PCs, mobile phones, and other portable devices [15,179]. The Bluetooth Special Interest Group (SIG) releases the Bluetooth specifications. Bluetooth specifications were established by the joint effort from over two thousand industry leading companies including 3Com, Ericsson, IBM, Intel, Lucent, Microsoft, Motorola, Nokia, Toshiba, etc. under the umbrella of Bluetooth SIG [39]. In addition, the IEEE 802.15 Working Group for Wireless Personal Area Networks approved its first WPAN standard derived from the Bluetooth Specification [134]. The IEEE 802.15.1 standard is based on the lower portions of the Bluetooth specification.

A Bluetooth unit, integrated into a microchip, enables wireless ad hoc communications, of voice and data between portable and/or fixed electronic devices like computers, cellular phones, printers, and digital cameras [130]. Due to its low-cost target, Bluetooth microchips may become embedded in virtually all consumer electronic devices in the future.

As a low cost, low power solution and with industry-wide support, Bluetooth wireless technology has already started to revolutionize the personal connectivity market by providing freedom from wired connections—enabling portable links between mobile computers, mobile phones, portable handheld devices, and connectivity to the Internet. Eventually, picocellular-based Personal Area Networks will able to provide services such as real-time voice and data in a much more economical way than in existing systems.

The Bluetooth system can manage a small number of low-cost point-to-point, and point to multi-point communication links over a distance of up to 10 m with a transmit power of less than 1 mW. It operates in the globally available unlicensed ISM (industrial, scientific, medical) frequency band at 2.4 GHz and applies frequency hopping for transmitting data over the air using a combination of circuit and packet switching.

From a logical standpoint, Bluetooth belongs to the contention-free token-based multi-access networks. Into a Bluetooth network, one station has the role of master, and all other Bluetooth stations are slaves. The master decides which slave is the one to have the access to the channel. More precisely, a slave is authorized to deliver a single packet to the master only if it has received a polling message from the master. The units that share the same channel (i.e., are synchronized to the same master) form a piconet, the fundamental building block of a Bluetooth network. A piconet has a bit rate of 1 Mbit/s that represents the channel capacity including the overhead introduced by the adopted protocols, and polling scheme. A piconet contains a master station, and up to seven *active* (i.e., participate in data exchanging) slaves, contemporarily.

Inside a piconet, Bluetooth stations can establish up to three 64 Kbit/s synchronous (voice) channels or an asynchronous (data) channel supporting data rates of maximal 723 Kbit/s asymmetric or 433 Kbit/s symmetric. A detailed presentation of Bluetooth characteristics can be found in [15,48,179]. The performance of a Bluetooth piconet is investigated in [27], the impact of the intra-piconet scheduling algorithm is documented in [27]. Bluetooth performance when used for accessing the Internet is analyzed in [25].

A piconet constitutes a single-hop Bluetooth ad hoc network. Multi-hop Bluetooth networks can be obtained by interconnecting several piconets. The Bluetooth specification defines a method for piconet interconnection: *the scatternet*. While the current Bluetooth specification defines the notion of a scatternet, it does not provide the mechanisms to construct it. A scatternet can be dynamically constructed, in an ad hoc fashion, when some nodes belong (at the same time) to more than one piconet, i.e., inter-piconet units. The traffic between two piconets is delivered through the common node(s). The scatternet formation algorithm constitutes a hot research issue. Solutions proposed in the literature can be subdivided in two classes: single-hop and multi-hop topologies [22]. Single-hop solutions assume that all Bluetooth devices are in each other transmission range (see e.g., [169,185,237]). Among solutions that apply to the more general case of multi-hop topologies, some schemes generate a tree-like scatternet starting from a designated node, named blueroot [291]. Other schemes produce topologies different from a tree [135,173,208,278]. The protocol proposed in [135,173] builds up a connected scatternet in which each piconet has no more than seven slaves, but requires that each node be equipped with additional hardware that provides to each node with its current geographic location (e.g., a GPS receiver). The BlueStars protocol [208] proceeds in three phases: the discovery device phase, the piconets' formation, and the configuration of the piconet into a connected scatternet. Piconets formation exploits a clustering-based approach for the master selection. A multi-phase protocol is also implemented by the BlueNet protocol [278] but it does not guarantee a connected scatternet even when the topologies after the discovery device are connected. Ref. [23] presents a comparison of the solutions presented in [135,173,208,278]. Finally, the BlueMesh scatternet formation protocol [207] improves previous solutions from several perspectives: it requires no additional hardware, it guarantees up to seven slaves per piconet, and the generated scatternet is more robust.

A node can be synchronized with only a single piconet at time, and hence it can be active in more piconets only in a time-multiplexed mode. As the inter-piconet traffic must go through the inter-piconet units, the presence of the inter-piconet units, in all the piconets they belong to, must be scheduled in an efficient way [228].

Capacity assignment protocols constitute the link between scatternet-formation protocols, and scatternet scheduling protocols. Once the scatternet is formed, capacity assignment protocols operate to determine the capacities of the scatternet links that satisfy the traffic requirements [298].

4.2. IEEE 802.11 networks

In 1997, the IEEE adopted the first wireless local area network standard, named IEEE 802.11, with data rates up to 2 Mbps [131]. Since then, several task groups (designated by the letters from 'a', 'b', 'c', etc.) have been created to extend the IEEE 802.11 standard. Task groups' 802.11b and 802.11a have completed their work by providing two relevant extensions to the original standard [133], which are often referred to with the friendly name of Wireless Fidelity (Wi-Fi). The 802.11b task group produced a standard for WLAN operations in 2.4 GHz band, with data rates up to 11 Mbps and backward compatibility. This standard, published in 1999, has become an "overnight success", with several IEEE 802.11b products available on the market currently. The 802.11a task group created a standard for WLAN operation in the 5 GHz band, with data rates up to 54 Mbps. Among the other task groups, it is worth mentioning the task group 802.11e (attempting to enhance the MAC with QoS features to support voice and video over 802.11 networks), and the task group 802.11g (that is working to develop a higher speed extension to the 802.11b).

The IEEE 802.11 standard defines two operational modes for WLANs: *infrastructure-based* and *infrastructure-less* or *ad hoc*. Network interface cards can be set to work in either of these modes but not in both simultaneously. Infrastructure mode resembles cellular infrastructure-based networks. It is the mode commonly used to construct the so-called Wi-Fi hotspots, i.e., to provide wireless access to the Internet. In the ad hoc mode, any station that is within the transmission range of any other, after a synchronization phase, can start communicating. No AP is required, but if one of the stations operating in the ad hoc mode has a connection also to a wired network, stations forming the ad hoc network gain wireless access to the Internet.

The IEEE 802.11 standard specifies a MAC layer and a Physical Layer for WLANs. The PHY layer uses either direct sequence spread spectrum (ISM band, 2.4–2.4835 GHz), frequency-hopping spread spectrum, or infrared (IR) pulse position modulation (300–428,000 GHz) to transmit data between nodes. Infrared is more secure to eavesdropping, because IR transmissions require absolute line-of-sight links, contrary to radio frequency transmissions, which can penetrate walls and be intercepted by third parties unknowingly. However, infrared transmissions are more receptive to interference, e.g., sunlight [280].

The MAC layer offers two different types of service: a contention-free service provided by the *Distributed Coordination Function* (DCF), and a contention-free service implemented by the *Point Coordination Function* (PCF). The PCF is implemented on top of DCF and is based on a polling scheme. It uses a *Point Coordinator* that cyclically polls stations, giving them the opportunity to transmit. Since the PCF cannot be adopted in the ad hoc mode, hereafter it will not be considered. The DCF provides the basic access method of the 802.11 MAC protocol and is based on a *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) scheme. According to this scheme, when a node receives a packet to be transmitted, it first listens to the channel to ensure no other node is transmitting. If the channel is clear, it then transmits the packet. Otherwise, it chooses a random "back-off value" which determines the amount of time the node must wait until it is allowed to transmit its packet. During periods in which the channel is clear, the node decrements its backoff counter. When the backoff counter reaches zero, the node transmits the packet. Since the probability that two nodes will choose the same backoff factor is small, the probability of packet collisions, under normal circumstances, is low.

In WLAN, there is usually just one antenna for both sending and receiving, and hence the stations are not able to listen while sending. For this reason, in the CSMA/CA scheme there is no collision detection capability. Acknowledgment packets (ACK) are sent, from the receiver to the sender, to confirm that packets have been correctly received.

As no collision detection mechanism is present, colliding stations always complete their transmissions, severely reducing channel utilization, as well as throughput [50], thus presenting new challenges to conventional CSMA/CD-based MAC protocols. Several works have shown that an appropriate tuning of the IEEE 802.11 backoff algorithm can significantly increase the protocol capacity [33,51,276]. The basic idea is that the random backoff duration, before attempting to transmit the packet, should be dynamically tuned by choosing the contention window size as a function of the network congestion. By following this approach, the authors in [26] define and evaluate an extension to the IEEE 802.11 protocol to optimize protocol capacity and energy consumption, showing also that the optimal capacity state, and the optimal energy consumption state almost coincide.

In wireless ad hoc networks that rely on a carrier-sensing random access protocol, such as the IEEE 802.11, the wireless medium characteristics generate complex phenomena such as the hidden-station and the exposed-station problems. [4]

The hidden-station problem occurs when two (or more) stations, say A and C, cannot detect each other's transmissions (due to being outside of each other transmission range) but their transmission ranges are not disjoint [263]. As shown in Fig. 4, a collision may occur, for example, when the station A and station C start transmitting towards the same receiver, station B in the figure.

A *virtual carrier-sensing* mechanism based on the RTS/CTS mechanism has been included in the 802.11 standard to alleviate the hidden-terminal problem that may occur by using the *physical carrier sensing* only. Virtual carrier sensing is achieved by using two control frames, *Request To Send* (*RTS*) and *Clear To Send* (*CTS*), before the data transmission is actually taken place. Specifically, before transmitting a data frame, the source station sends a short control frame, named RTS, to the receiving station announcing the upcoming frame transmission. Upon receiving the RTS

[4] Hereafter, the words hidden-terminal and exposed-terminal will be interchanged with the words hidden-station and exposed-station, respectively.

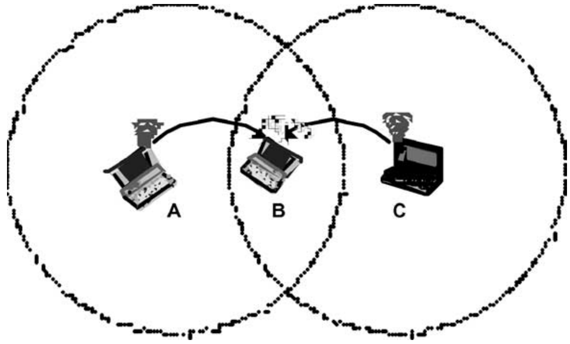

Fig. 4. Hidden-station problem.

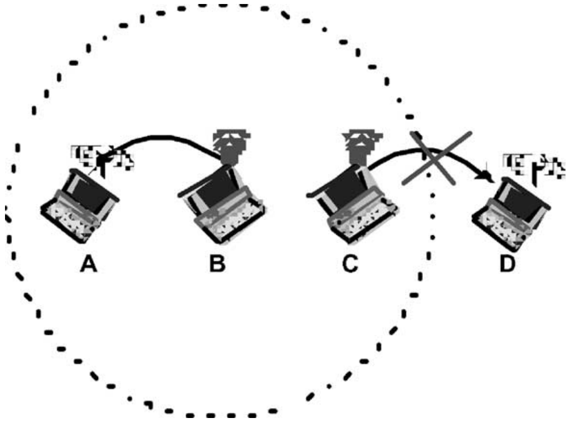

Fig. 5. Exposed-station problem.

frame, the destination station replies by a CTS frame to indicate that it is ready to receive the data frame. Both the RTS and CTS frames contain the total duration of the transmission, i.e., the overall time interval needed to transmit the data frame and the related ACK. This information can be read by any station within the transmission range of either the source or the destination station. Hence, stations become aware of transmissions from hidden station, and the length of time the channel will be used for these transmissions.

The exposed-terminal problem results from situations where a permissible transmission from a mobile station (sender) to another station has to be delayed due to the irrelevant transmission activity between two other mobile stations within sender's transmission range.

Fig. 5 depicts a typical scenario where the "exposed station" problem may occur. Let us assume that station A and station C can hear transmissions from B, but station A cannot hear transmissions from C. Let us also assume that station B is transmitting to station A, and station C has a frame to be transmitted to D. According to the CSMA scheme, C senses the medium and finds it busy because of B's transmission, and therefore refrains from transmitting to D, although this transmission would not cause a collision at A. The "exposed station" problem may thus result in loss of throughput.

It is worth pointing out that the hidden-station and the exposed-station problems are correlated with the *Transmission Range* (*TX_range*). *TX_range* is the range (with respect to the transmitting station) within which a transmitted packet can be successfully received. The transmission range is mainly determined by the transmission power and the radio propagation properties. By increasing the *Transmission Range*, hidden-station problem occurs less frequently, while the exposed station problem becomes more important as the *TX_range* identifies the area affected by a single transmission. In addition to the *Transmission Range*, also the *Physical Carrier Sensing Range* and the *Interference Range* must be considered to correctly understand the behavior of wireless (ad hoc) networks:

- the *Physical Carrier Sensing Range* (*PCS_range*) is the range (with respect to the transmitting station) within which the other stations detect a busy channel. It mainly depends on the sensitivity of the receiver (the receive threshold) and the radio propagation properties.
- The *Interference Range* (*IF_range*) is the range within which a station in receive mode will be interfered with by a transmitter, and thus suffer a loss. More precisely, a transmitting station A can interfere with a receiving station B if A is within the B interference range. The interference range is usually larger than the transmission range, and is a function of the path loss model.

Altogether, the *TX_range, PCS_range*, and *IF_range* define the relationships existing among 802.11 stations, when they transmit or receive.

4.2.1. Ad hoc networking

Original 802.11 standardization efforts concentrated on solutions for infrastructure-based WLANs, while little or no attention was given to the ad hoc mode. Currently, the widespread use of IEEE 802.11 cards makes this technology the most interesting off-the-shelf enabler for ad hoc networks [293]. This generated an extensive literature to investigate the performance of the 802.11 MAC protocol in the ad hoc environment. These studies have been pointed out several performance problems [4]. Most of the problems are due to the interaction of wireless channel characteristics (e.g., hidden- and exposed-station problems), 802.11 MAC protocol (mainly the back-off scheme) and TCP mechanisms (congestion control and time-out). As these problems are strictly connected with TCP, we defer an in depth discussion to Section 5.3 where we analyze TCP issues in mobile ad hoc networks. In the remaining part of this section, we will focus on the analysis of measurements taken from small ad hoc testbeds [3,4].

Most of the existing results in this area are based on simulative studies whose accuracy depends on the assumptions performed in the 802.11 simulation models (e.g., *TX_range, PCS_range*, and *IF_range*). Measurements' studies have therefore an important role in confirming simulative observations and understanding the behavior of IEEE 802.11 ad hoc networks. Experimental results presented in [3,4] provide important indications in that they:

(i) confirm results obtained from simulative studies. Specifically, results indicate that TCP connections may actually experience significant throughput unfairness, and even capture of the channel by one of the connections;
(ii) point out several aspects of 802.11b standard that are commonly neglected in simulation studies. These include: the differences in the transmission ranges between data and control frames, and the differences between the transmission ranges measured in the testbeds and the *TX_range* values commonly used in the network simulators.

Table 1
Transmission ranges at different data rates

	11 Mbps	5.5 Mbps	2 Mbps	1 Mbps
TX_range	30 m	70 m	90–100 m	110–130 m

Regarding point (ii), Table 1 summarizes the measurements presented in [3,4]. It is worth noting that simulation studies are typically performed assuming a 2 Mbps channel with *TX_range* values ranging from 250 m [200] to 376 m [109].

4.3. MAC protocol research issues

Bluetooth and IEEE 802.11 technologies exemplify the two main categories in which multiple access networks can be categorized [123] into: random access (e.g., CSMA, CSMA/CD) and controlled access (e.g., TDMA, token passing schemes, etc.). The lack of an infrastructure, and the peer-to-peer nature of ad hoc networking, make random access protocols the natural choice for medium access control in ad hoc networks. Indeed, most proposals of MAC protocols for ad hoc networks are based on the random access paradigm; in addition, the CSMA/CA scheme was selected (due to the inherent flexibility of this scheme) by the IEEE802.11 committee as the basis for its standards. On the other hand, demand assignment access schemes (even though generally more complex) are more suitable for environments that need guarantees on the Quality of Service (QoS) perceived by its users. The Bluetooth technology that is designed to support, beyond data traffic, also delay sensitive applications (e.g., voice) adopts a TDMA scheme with an implicit token-passing scheme for the slots' assignment inside a piconet.

Bluetooth and IEEE 802.11 have been designed for single-hop WPANs and WLANs, respectively, and their use in a multi-hop environment is not optimized. The design of MAC protocols for a multi-hop ad hoc environment is a hot research issue. In the following subsections we summarizes the ongoing research activities in this field.

4.3.1. Random access MAC protocols

In recent years a large number of random access MAC protocols have been developed to cope with problems that occur when random access protocol are used over wireless channels. A number of improved protocols such as MACA (multiple access with collision avoidance protocol), MACAW (MACA with CW optimization), FAMA (floor acquisition multiple access), MACA/PR and MACA-BI (multiple access with collision avoidance by invitation protocol) [31,95,146,160,260] have been proposed over the years to resolve the multi-access problems over wireless channels (mainly the hidden-station phenomena), and improve channel performance. MACAW is one of the more promising protocols in this area [31] MACAW has been proposed to extend MACA by adding link level ACKs and a less aggressive backoff policy [31]. RTS/CTS-based mechanism is the solution emerging from these studies. Several variations and analyses of the RTS/CTS scheme can be found in literature (see for example [31,96,105,108]), and an RTS/CTS mechanism is included in the 802.11 standard to reduce the impact of the hidden stations. This is achieved by reserving a large portion of the channel around the receiver and the sender, thus reducing the interference probability on the ongoing transmission. However, this mechanism, by reserving a large portion of the channel for a single transmission, increases the number of other nodes in the vicinity that remain blocked as they are exposed to this single transmission. Indeed, by extending the area in which the (physical or logical) carrier sensing is effective the hidden-station phenomenon is diminished, while the exposed stations phenomenon increases.

It is also worth noting that most of the proposed random access protocols have been designed by taking into account the transmission range only, without considering the fact that physical carrier sensing is typically much larger. If the PCS_Range is about twice the TX_Range (see for example the model of the 802.11 physical layer implemented in NS-2 [200] and Glomosim [109]), the stations that are in the TX_Range of the receiver will observe the channel busy when a sender-to-receiver transmission occurs, and hence there is no need to use the virtual carrier sensing implemented by the CTS packet. A similar observation applies for the receiver-to-sender ACK transmission. These observations have also been confirmed by experimental results indicating that phenomena occurring at the physical layer make the physical carrier sensing effective even if the transmitting stations are "apparently hidden" from each other [48].

A more careful understanding of the phenomena that occur at the physical layer, and that can impact the MAC design, is fundamental for designing random access protocols that can efficiently operate in multi-hop ad hoc networks where the status of the channel observed by a given station A is affected (at the same time) by several other stations. The type of impact being a function of the stations' location in the transmission range, interference range or physical carrier-sensing range of station A. Furthermore, the number of interfering stations and their impact change dynamically.

To summarize, while solutions exist for solving the hidden-station phenomena, several other issues still need to be addressed, the exposed stations phenomenon being one of the most important. In addition, the existence of physical and interference ranges larger than the transmission range must be carefully considered in the MAC design.

Seedex [226] is an interesting approach to avoid collisions and the hidden-station problem without making explicit channel reservations. Seedex assumes a slotted channel, and its key idea is to define, at each station, a random transmission schedule (i.e., the node will use the channel slots according a Bernoulli process with parameter p) that is then propagated to the two-hop neighbors. In this way, all nodes are aware of the transmissions scheduled by their two-hop neighbors, and hence can tune their transmission parameters to optimize the channel throughput. The publishing of stations' random schedules is achieved in a very efficient way by summarizing it through a sequence of pseudo-random numbers. By exploiting the properties of pseudo-random number generators [156,165], publishing a node scheduler can be simply translated to publishing the seed of its pseudo-random number generator.

A novel and promising direction for reducing the interference among stations and the exposed-station phenomenon, is based on the use of directional antennas [222]. Research in wireless ad hoc networks typically assumes the use of omni-directional antennas at all nodes. With omni-directional antennas, while two nodes are communicating using a given channel, the MAC protocol (e.g., IEEE 802.11) requires that all other nodes in the vicinity stay silent. With directional antennas, two pairs of nodes located in each other's vicinity may potentially simultaneously access the channel, depending on the directions of transmission. Directional antennas can adaptively select radio signals of interest in specific directions, while filtering out unwanted interference from other directions. This can increase spatial reuse of the wireless channel. In addition, the higher power gain of directional antennas (with respect to omni-directional antennas) extends the node transmission range [221].

Ref. [78] extends the 802.11 MAC for using it with directional antennas. The basic protocol, named Directional MAC (DMAC) operates in two phases. The first phase (based on RTS/CTS exchange) is used for tuning the receiver antenna on the sender direction. During the first phase, the receiver listens to the channel omni-directionally. After this phase, directional transmissions are used. Similar schemes have been proposed in [265]. MMAC [78] extends the basic DMAC protocol by using multi-hop RTSs to establish a directional link between sender and receiver, then CTS, DATA and ACK are transmitted over a single hop by exploiting the directional antennas gain. The Receiver-Oriented Multiple Access protocol [34] exploits the multi-link feature of directional antennas. In this protocol a node can commence several simultaneous communication sessions by forming up to K links, where K indicates the number of antenna beams.

The work in [222] presents an updated, and in depth analysis of the state of the art of antenna beamforming and power control in ad hoc networks. The author points out the most significant problems related to the introduction of beamforming and power control in the ad hoc scenario, and identifies which are (from the MAC layer perspective) the most relevant gains in system performance.

Finally, beyond collision avoidance, other optimization studies have been done at the MAC layer level to improve MANET performance, including MAC improvement, algorithms used to reduce mobile node energy consumption [73], and the use of power control for improving power saving at MAC level, see [144] and the references herein.

4.3.2. Controlled access MAC protocols

Several controlled access schemes exist, e.g., TDMA, CDMA, token-passing, etc. [123]. Among these, TDMA is the most commonly used in ad hoc networks. In the TDMA approach, the channel is generally organized in frames, where each frame contains a fixed number of time slots. The mobile hosts negotiate a set of TDMA slots in which to transmit. If a centralized controller exists, it is in charge of assigning the slots to the nodes in the area it controls. In this way transmissions are collisions' free, and it is possible to schedule node transmissions according to fairness and QoS criteria. TDMA has been adopted, for example, in cluster-based multi-hop ad hoc networks (see Section 5.2.4 on clustering), where the clusterhead assigns the time slots to the nodes of its cluster taking into consideration their bandwidth requirements. The absence of collisions, and an appropriate scheduling for slots assignment guarantee bounded delays [113]. In a mobile network environment the re-assignment of slots after topology changes makes a legacy TDMA scheme very inefficient. These inefficiencies can be avoided in an elegant way by applying the Time Spread Multiple Access (TSMA) protocol. This algorithm uses only global network parameters (the number of nodes in the network and the maximum number of neighbors each node may have) to define the slots' assignment to nodes, in this way no re-computation is required due to nodes mobility. Specifically, with TSMA, multiple slots are assigned to each node inside a frame. Collisions may occur while a node is transmitting inside its assigned slots, but by exploiting the properties of finite fields, the TSMA scheme guarantees a collision-free transmission slot to each neighbor within a single frame [57]. This algorithm is mainly suitable for ad hoc networks with thousands of nodes with a sparse topology. A similar method is presented in [139]. The main limitation of TSMA-like schemes is that the global network parameters are generally unknown and difficult to predict. For this reason, distributed algorithms that work with a partial knowledge of the network status (e.g., number of neighbors) appear more suitable for dynamic ad hoc networks [72,292]. Dynamic protocols typically operate in two phases. In the first phase a dedicated set of slots is used (on a contention basis) for making slots' reservations. After a successful contention, a node can access one or more transmission slots.

5. Networking

To cope with the self-organizing, dynamic, volatile, peer-to-peer communication environment in a MANET, most of the main functionalities of the *Networking protocols* (i.e., network and transport protocols in the Internet architecture) need to be re-designed. In this section we provide an outline of the main research issues in these areas, and survey the existing literature.

The aim of the networking protocols is to use the one-hop transmission services provided by the enabling technologies to construct end-to-end (reliable) delivery services, from a sender to one (or more) receiver(s). To establish an end-to-end communication, the sender needs to locate the receiver inside the network. The purpose of a *location service* is to dynamically map the logical address of the (receiver) device to its current location in the network. Current solutions generally adopted to manage mobile terminals in infrastructure networks are generally inadequate, and new approaches have to be found.

Once, a user is located, *routing and forwarding algorithms* must be provided to route the information through the MANET. Finally, the low reliability of communications (due to wireless communications, users' mobility, etc.), and the possibility of network congestion require a *redesign of Transport Layer mechanisms*.

In this section, we survey these various aspects of the research on networking protocols, i.e., location service (Section 5.1), routing and forwarding (Section 5.2), and TCP (Section 5.3).

5.1. Location services

A Location Service answers queries about nodes' location. In legacy mobile networks [158] (e.g., GSM, Mobile IP), the presence of a fixed infrastructure led to the diffusion of two-tier schemes to track the position of mobile nodes. Examples are the Home Location Register/Visitor Location Register approach used in GSM networks, and the Home Agent/Foreign Agent approach for Mobile IP networks. Efficient implementations of these approaches use centralized servers. In a mobile ad hoc network, these solutions are not useful, and new approaches have to be found for mobility management [198].

A simple solution to node location is based on flooding the location query through the network. Of course, flooding does not scale, and hence this approach is only suitable for limited size networks, where frequently flooded packets have only a limited impact on network performance. Controlling the flooding area can help to refine the technique. This can be achieved by gradually increasing, until the node is located, the number of hops involved in the flooding propagation.

The flooding approach constitutes a reactive location service in which no location information is maintained inside the network. The location-service maintenance cost is negligible, and all the complexity is associated with query operations. On the other hand, proactive location services subdivide the complexity in the two phases. Proactive services construct and maintain inside the network data structures that store the location information of each node. By exploiting the data structures, the query operations are highly simplified.

DREAM [30] is an example of a proactive location service in which all the complexity is in the first phase. All the network nodes maintain the location information of all the other nodes. To this end, each node uses the flooding technique to broadcast its location. To reduce the overhead, a node can control the frequency with which its sends its position-update messages, and the area (number of hops) to which the update messages are delivered. In this way, the location information accuracy decreases with the distance from the node but this shortcoming is balanced by the *distance* *effect*: "the greater the distance separating two nodes, the slower they appear to be moving with respect to each other" [30].

The location services presented in [106,136,164, 213] select for each node a subset of network nodes that are designed to store its location. These works follow two main approaches: *virtual home* and *grid*.

Refs. [106,136] use a similar approach to implement the home location server of a node by distributing this function on several nodes inside the ad hoc networks. Specifically, each node is univocally associated with an area inside the ad hoc network (i.e., its *virtual home*) in which its information is stored. The association between a node and its virtual home area is obtained through a hash function (known to all nodes) applied to the node identifier. The query related to a node location is therefore directed to its *virtual home* where the node information is stored.

Refs. [164,213] assume that a grid-like structure is superposed on the ad hoc network. By exploiting the grid structure the location service is organized in a hierarchy of squares that simplifies the update and query operations. For example, in [164], the grid hierarchy and the node identifiers define for each mobile node a small set of other nodes (its location servers) designed to contain its current location. A node has no knowledge of the identity of its location servers, but the protocol defines a distributed and independent procedure to identify them. A node only forwards its position updates toward grid squares. Then, locally to each selected grid square, the distributed procedure finds one location server for that node. The same distributed procedure is also used to locate the node location server to solve the queries.

Ref. [112] contains an updated overview of Location Services for ad hoc networks.

5.2. Ad hoc routing and forwarding

The highly dynamic nature of a mobile ad hoc network results in frequent and unpredictable changes of network topology, adding difficulty and complexity to routing among the mobile nodes. The challenges and complexities, coupled with the critical importance of routing protocol in establishing communications among mobile nodes, make routing area the most active research area within the MANET domain. Numerous routing protocols and algorithms have been proposed, and their performance under various network environments, and traffic conditions have been studied and compared.

Several surveys and comparative analysis of MANET routing protocols have been published [88,233]. Ref. [205] provides a comprehensive overview of routing solutions for ad hoc network, while an updated and in depth analysis of routing protocols for mobile ad hoc network is presented in [88].

A preliminary classification of the routing protocols can be done via the type of cast property, i.e., whether they use a *Unicast*, *Geocast*, *Multicast*, or *Broadcast* forwarding [217].

Broadcast is the basic mode of operation over a wireless channel; each message transmitted on a wireless channel is generally received by all neighbors located within one-hop from the sender. The simplest implementation of the broadcast operation to all network nodes is by naive flooding, but this may cause the *broadcast storm problem* due to redundant re-broadcast [203]. Schemes have been proposed to alleviate this problem by reducing redundant broadcasting. Ref. [252] surveys existing methods for flooding a wireless network intelligently.

Unicast forwarding means a one-to-one communication, i.e., one source transmits data packets to a single destination. This is the largest class of routing protocols found in ad hoc networks.

Multicast routing protocols come into play when a node needs to send the same message, or stream of data, to multiple 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. Nodes may join or leave a multicast group as desired, on the other hand, nodes can join or leave a geocast group only by entering or leaving the corresponding geographical region. 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 towards a geographical position, constitute the basis for constructing geocasting delivery services.

This section presents the various aspects of routing algorithms. Sections 5.2.1 and 5.2.2 provide an overview of unicast and multicast routing protocols, respectively. Position-based routing algorithms are discussed in Section 5.2.3. Finally, in Section 5.2.4 we present the clustering techniques used to construct a hierarchy inside an ad hoc network to increase the scalability of networking functions.

5.2.1. Unicast routing

A primary goal of unicast routing protocols is the correct and efficient route establishment and maintenance between a pair of nodes, so that messages may be delivered reliably and in a timely manner. This is the target of classical Internet link-state (e.g., OSPF) and distance-vector (e.g., RIP) routing protocols [234], but MANET characteristics make the direct use of these protocols infeasible [257]. Internet protocols have been designed for networks with almost static topologies (therefore unable to keep pace with frequent link changes in ad hoc environment), where routing protocols run in specialized nodes with plentiful resources, i.e., energy, memory, processing capability, etc. On the other hand, MANET routing protocols must operate in networks with highly dynamic topologies where routing algorithms run on resource-constrained devices. Providing routing protocols for MANETs has been, in the last 10 years, perhaps the most active research area for the ad hoc network community. A large number of routing protocols have been designed, either by modifying Internet routing protocols, or proposing new routing approaches. The number of proposed protocols is too large to be surveyed in this article. Below, we therefore present a high-level classification of MANET routing protocols, and then sketch some representative protocols for each class. More details on MANET routing protocols can be found in [18,88,233].

MANET environment and characteristics, such as mobility and bandwidth/energy limitations, led to defining a set of desirable characteristics that a routing protocol should have to optimize the limited resources (i.e., minimal control overhead, minimal processing overhead, and loop freedom/prevention to avoid wasting resources due to packets spinning around in the network), and cope with dynamic topologies (efficient dynamic topology establishment and maintenance, rapid route convergence, and possibly supporting multiple routes). Other important features for a routing protocol are: scalability, supporting unidirectional links, security and reliability, Quality of Service support [65,88,182].

MANET routing protocols are typically subdivided into two main categories: *proactive routing protocols and reactive on-demand routing protocols* [233]. 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. As the routing information is usually maintained in tables, these protocols are sometimes referred to as Table-Driven protocols. Reactive on demand routing protocols, on the other hand, establish the route to a destination only when there is a demand for it. The source node through the route discovery process usually initiates the route requested. Once a route has been established, it is maintained until either the destination becomes inaccessible (along every path from the source), or until the route is no longer used, or expired [88,233].

PROACTIVE ROUTING PROTOCOLS. The main characteristic of these protocols is the constant maintaining of a route by each node to all other network nodes. The route creation and maintenance are performed through both periodic and event-driven (e.g., triggered by links breakages) messages. Representative proactive protocols are [88,233]: Destination-Sequenced Distance-Vector (DSDV), Optimized Link State Routing (OLSR), and Topology Dissemination Based on Reverse-Path Forwarding (TBRPF).

The Destination-Sequenced Distance-Vector (DSDV) protocol [206] is a distance-vector protocol with extensions to make it suitable to MANET. Every node maintains a routing table with one route entry for each destination in which the shortest path route (based on number of hops) is recorded. To avoid routing loops, a destination sequence number is used. A node increments its sequence number whenever a change occurs in its neighborhood. This number is used to select among alternative routes for the same destination. Nodes always select the route with the greatest number, thus selecting the most recent information [206].

CGSR extends DSDV with clustering (see Section 5.2.4) to increase the protocol scalability [77]. In addition, heuristic methods like priority token scheduling, gateway code scheduling, and path reservation [77] are used to improve the protocol's performance. Unfortunately, setting up the structure in a highly dynamic environment can adversely affect protocol performance since the structure might not persist for a very long time.

WRP is another loop-free proactive protocol where four tables are used to maintain distance, link cost, routes and message retransmission information [186]. Loop avoidance is based on providing for the shortest path to each destination both the distance and the second-to-last hop (predecessor) information.

Despite the variance in the number of routing tables used, and the difference in routing information maintained in these tables, proactive routing protocols like DSDV, CGSR and WRP are all distance vector shortest-path based, and have the same degree of complexity during link failures and additions.

OLSR protocol [142] is an optimization for MANET of legacy link-state protocols. The key point of the optimization is the *multipoint relay* (MPR). Each node identifies (among its neighbors) its MPRs. By flooding a message to its MPRs, a node is guaranteed that the message, when retransmitted by the MPRs, will be received by all its two-hop neighbors. Furthermore, when exchanging link-state routing information, a node lists only the connections to those neighbors that have selected it as MPR, i.e., its Multipoint Relay Selector set. The protocol selects bi-directional links for routing, hence avoiding packet transfer over unidirectional links.

Like OLSR, TBRPF [43] is a link-state routing protocol that employs a different overhead reduction technique. Each node computes a shortest-path tree to all other nodes, but to optimize bandwidth only part of the tree is propagated to the neighbors, for details see [88].

The FSR protocol [151,211] is also an optimization over link-state algorithms using fisheye technique. In essence, FSR propagates link state information to other nodes in the network based on how far away (defined by scopes which are determined by number of hops) the nodes are. The protocol will propagate link state information more frequently to nodes that are in a closer scope, as opposed to ones that are further away. This means that a route will be less accurate the further away the node is, but once the message gets closer to the destination, the accuracy increases. LANMAR [212,258] builds on top of FSR and achieves hierarchical routing by partitioning the network nodes into different mobility groups; a landmark node is elected within each group to keep track of which logical subnet a node belongs to, and facilitate inter-group routing; FSR is used for intra-group routing.

Reactive Routing Protocols. These protocols depart from the legacy Internet approach. To reduce the overhead, the route between two nodes is discovered only when it is needed. Representative reactive routing protocols include: Dynamic Source Routing (DSR), Ad hoc On Demand Distance Vector (AODV), Temporally Ordered Routing Algorithm (TORA), Associativity Based Routing (ABR), Signal Stability Routing (SSR).

DSR is a loop-free, source based, on demand routing protocol [141], where each node maintains a route cache that contains the source routes learned by the node. The route discovery process is only initiated when a source node do not already have a valid route to the destination in its route cache; entries in the route cache are continually updated as new routes are learned. Source routing is used for packets' forwarding.

AODV is a reactive improvement of the DSDV protocol. AODV minimizes the number of route broadcasts by creating routes on-demand [218], as opposed to maintaining a complete list of routes as in the DSDV algorithm. Similar to DSR, route discovery is initiated on-demand, the route request is then forward by the source to the neighbors, and so on, until either the destination or an intermediate node with a fresh route to the destination, are located.

DSR has a potentially larger control overhead and memory requirements than AODV since each DSR packet must carry full routing path information, whereas in AODV packets only contain the destination address. On the other hand, DSR can utilize both asymmetric and symmetric links during routing, while AODV only works with symmetric links (this is a constraint that may be difficult to satisfy in mobile wireless environments). In addition, nodes in DSR maintain in their cache multiple routes to a destination, a feature helpful during link failure. In general, both AODV and DSR work well in small to medium size networks with moderate mobility.

TORA is another source-initiated on-demand routing protocol built on the concept of link reversal of the Directed Acyclic Graph (ACG) [209]. In addition to being loop-free and bandwidth efficient, TORA has the property of being highly adaptive and quick in route repair during link failure, while providing multiple routes for any desired source/destination pair. These properties make it especially suitable for large, highly dynamic, mobile ad hoc environments with dense nodes' populations. The limitation in TORA's applicability comes from its reliance on synchronized clocks. If a node does not have a GPS positioning system, or some other external time source, or if the time source fails, the algorithm fails.

ABR protocol is also a loop free protocol, but it uses a new routing metric termed *degree of association stability* in selecting routes, so that route discovered can be longer-lived route, thus more stable and requiring less updates subsequently. The limitation of ABR comes mainly from a periodic beaconing used to establish the association stability metrics, which may result in additional energy consumption. Signal Stability Algorithm (SSA) [79] is basically an ABR protocol with the additional property of routes' selection using the signal strength of the link.

In general, on-demand reactive protocols are more efficient than proactive ones. On-demand protocols minimize control overhead and power consumption since routes are only established when required. By contrast, proactive protocols require periodic route updates to keep information current and consistent; in addition, maintain multiple routes that might never be needed, adding unnecessary routing overheads.

Proactive routing protocols provide better quality of service than on-demand protocols. As routing information is constantly updated in the proactive protocols, routes to every destination are always available and up-to-date, and hence end-to-end delay can be minimized. For on-demand protocols, the source node has to wait for the route to be discovered before communication can happen. This latency in route discovery might be intolerable for real-time communications.

Ref. [233] presents a set of tables that summarize the difference among these various protocols in terms of the complexity, route update patterns and capabilities. The above considerations point to proactive protocols being suitable for small-scale static networks, while reactive protocols, such as DSR and AODV can normally work well in medium size networks with moderate mobility [88]. In the last few years, according to these observations, more attention was given to reactive protocol design, as they result in a more scalable solution. However, a novel perspective on the overhead of routing protocols is presented in [247,251]. Here the authors consider also the effect introduced by the sub-optimality of routes, accounted for as the additional bandwidth required for using a sub-optimal path. From this perspective, the authors formulate an analytical model whose solution opens a design space for scalable link-state routing strategies based on limited dissemination of link-state information.

In addition to proactive and reactive protocols, another class of unicast routing protocols that can be identified is that of: *hybrid protocols*. The Zone-Based Hierarchical Link State Routing Protocol (ZRP) [124] is an example of hybrid protocol that combines both proactive and reactive approaches thus trying to bring together the advantages of the two approaches. ZRP defines around each node a *zone* that contains the neighbors within a given number of hops from the node. Proactive and reactive algorithms are used by the node to route packets within and outside the zone, respectively.

5.2.2. Multicasting

Multicasting is an efficient communication service for supporting multi-point applications (e.g., software distributions, audio/video conferencing) in the Internet. In MANET, the role of multicast services is potentially even more important due the bandwidth and energy savings that can be achieved through multicast packets' delivery [76].

MANET multicast research started by adapting Internet existing approaches to ad hoc networks. Two main approaches are used for multicast routing in fixed networks: group-shared tree and source-specific tree. In both cases, multicast trees are constructed to interconnect all the members of the multicast group. Data is delivered along the tree paths to reach all group members. The source-specific approach maintains, for each source, a tree towards all its receivers. In the group-share, a single tree is constructed for the whole group (e.g., regardless the sources location). Internet multicast routing protocols works well under static configurations; supporting multicast route under highly dynamic network configurations is a big challenge for ad hoc networking researchers [62]. Several multicast protocols for ad hoc networks based on trees have been proposed by adapting those existing for fixed networks. Representative tree-based multicast protocols are Multicast AODV (MAODV) [229] and AMRIS [277]. Both protocols are an on-demand, and construct a shared delivery tree to support multiple senders and receivers within a multicast session. Energy-efficient algorithms for the construction of multicast trees are proposed and evaluated in [275].

The topology of a wireless mobile network can be very dynamic, and hence the maintenance of connected multicast routing tree may cause large overheads. To avoid this, a different approach based on meshes has been proposed. Meshes are more suitable for dynamic environments because they support more connectivity than trees, thus avoiding drawbacks of multicast trees, e.g., intermittent connectivity, traffic concentration, or frequent tree reconfiguration. Although multicast meshes perform better than multicast trees in dynamic networks, mesh mechanism is more inclined to form routing loops; in addition, approaches to mesh building based on flooding incurs excessive overhead in large networks [187].

Representative mesh-based multicast routing protocols include: Core-Assisted Mesh Protocol (CAMP) [187], and the On-demand Multicast Routing Protocol (ODMRP) [242]. These protocols build routing meshes to disseminate multicast packets within groups. The difference is that ODMRP uses flooding to build the mesh, while CAMP uses one or more core nodes to assist in building the mesh, instead of flooding.

To avoid the significant delay in route recovery caused by link failures, in [241] the authors explore the possibility of using a set of pre-calculated alternate trees. When a links break, another tree, which does not includes the failed link, is immediately utilized. An alternative approach to avoiding problems related to tree/mesh maintenance is implemented in the Explicit Multicasting protocol [138]. This protocol is designed to operate in a stateless manner where no intermediate node needs to maintain multicast forwarding paths.

5.2.3. Location-aware routing

Location-aware routing protocols use, during the forwarding operations, the nodes' position (i.e., geographical coordinates) provided by GPS [147] or other mechanisms [60,248]. Specifically, a node selects the next hop for packets' forwarding by using the physical position of its one-hop neighbors, and the physical position of the destination node. The packets are forwarded to a neighbor in the receiver direction; for this reason, these routing protocols are also referred to as position-based or geographic approaches. Generally, a location service is used to solve the queries about the current position of the networks' node.

Location-aware routing does not require routes' establishment and maintenance. No routing information is stored. The use of geo-location information avoids network-wide searches, as both control and data packets are sent towards the known geographical coordinates of the destination node. These features make location-aware routing protocols quickly adaptive to route changes, and more scalable than unicast protocols such as AODV, DSDV, DSR [110].

Three main strategies can be identified in location-aware routing protocols [274]: *greedy forwarding*, *directed flooding* and *hierarchical routing*. The basic idea behind these algorithms is to forward a packet towards node(s) that are closer to the destination, then itself. Greedy forwarding and directed flooding algorithms forward the packet to one or more neighbors, respectively. Hierarchical routing algorithms are a combination of position-based and non-position-based routing algorithms. Location-aware routing is typically used on long distances (i.e., when the forwarding node and the receiver are far away), while a non-position-based algorithm is used at local level (i.e., the packet is close to the receiver).

A large number of location-aware algorithms have been proposed in the literature (see [111], and the reference herein); hereafter we introduce some routing algorithms representative of the three classes. More details on these protocols can be found in [110,111,262,274].

Greedy Forwarding. In this type of strategies a node tries to forward the packet to one of its neighbors that is closer to the destination than itself. If more than one closer node exists, different choices are possible. If, on the other hand, no closer neighbor exists, new rules are included in the greedy strategies to find an alternative route. To select the next node, when more then one closer node exists, several policies have been proposed. The Most Forward within Radius (MFR) policy [264] maximizes the progress by forwarding the packets to the node closest to the destination. On the other hand, by taking into consideration that the transmission at the maximum distance implies the maximum transmission power (and hence the maximization of the collision probability with other nodes), the Nearest with Forward Progress (NFP) scheme [121] applies a selection of the next node that tries to maximize the success probability. NFP sends the packet to the node closer to the sender. The transmission can thus be accomplished with minimum power; hence the interference with the other nodes is minimized, while the probability of a successful transmission is maximized.

Finally, in the compass routing scheme [152] the next node is selected to minimize the spatial distance. In this scheme the packet is forwarded to the neighbor that is closer to the straight line joining the sender to the receiver.

Greedy policies enter into a deadlock when packet arrives at a node corresponding to a local optimum, i.e., no neighbor exists that is closer to the destination than the current forwarding node. To exit from the deadlock, greedy policies are supplemented with extra rules such as: the selection of the node with the least negative progress [264], and the discard of the packets that arrive at a local optimum [121]. In the former case, policies to avoid routing loops are also introduced.

By combining the above rules for the choice of the next neighbor and to exit from local optima, several routing algorithms (based on the greedy forwarding principle) have been defined. The GPRS and the *face* algorithms use the MFR scheme for selecting the next node. A greedy forwarding is applied up to a local optimum, then similar strategies are applied by the two algorithms to exit from this state, and finding a node that helps in progressing to the destination.

The geographical distance routing (GEDIR) uses both the MFR and the compass routing schemes. In addition, it uses rules to avoid loops and to exit from local optima [246].

Directed Flooding. With directed flooding nodes forward the packets to all neighbors that are located in the direction of the destination. DREAM [30] and LAR [153] are two routing algorithms that apply this principle. However, LAR uses directed flooding only for route discovery, while DREAM applies a restricted flooding for packets delivery. In the DREAM algorithm, the forwarding node, by using the information about the destination node's position, determines an expected region for the destination. The expected region is a circle centered on the last known receiver location, which represents the area where the receiver should be, taking into account the node mobility from its last known position. A packet is then forwarded toward the expected region. Similarly, LAR defines the expected zone in which the destination node is expected to be located. From the expected zone, the algorithm identifies a request zone. LAR floods the route-searching packets only inside the request zone.

Hierarchical Routing. The location proxy routing protocol (also referred to as Grid routing) [177], and the Terminode routing protocol [21] are hierarchical routing protocols in which routing is structured in two layer. Both protocols apply different rules to long- and short-distance routing, respectively. Location-aware routing is used for routing on long distances, while when a packet arrives close to the destination a proactive distance vector scheme is adopted.

5.2.4. Clustering

Any device with a microprocessor can in principle be an ad hoc network node. Supporting a large number of heterogeneous users is thus a requirement for future ad hoc networks. In a large network, flat routing schemes produce an excessive amount of information that can saturate the network. In addition, given the nodes heterogeneity, nodes may have highly variable amount of resources, and this naturally produces a hierarchy in their roles inside the network. Nodes with large computational and communication power, and powerful batteries are more suitable for supporting the ad hoc network functions (e.g., routing) than small embedded-systems.

Cluster-based routing is an interesting solution to address nodes heterogeneity, and to limit the amount of routing information that propagates inside the network. The basic idea behind clustering is to group the network nodes into a number of overlapping clusters. This enables the aggregation of the routing information, and consequently increases the routing algorithms scalability. Specifically, clustering makes possible a hierarchical routing in which paths are recorded between clusters (instead of between nodes); this increases the routes lifetime, thus decreasing the amount of routing control overhead [88].

Clustering was introduced in 1980s to provide distributed control in mobile radio networks [32]. 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 this one clusterhead, and gateways, i.e., nodes that can hear two or more clusterheads [32]. A simple clustering distributed algorithm is based on the nodes' identifier (ID). By assuming that a distinct ID is associated to each node, the node with the lowest ID (in a neighborhood) is elected as the clusterhead [113]. This guarantees that two clusterheads cannot hear each other. As all nodes in the cluster can hear the clusterhead, all inter-cluster communications occur in at most two hops, while intra-cluster communications occurs through the gateway nodes. Ordinary nodes send the packets to their clusterhead, that either distributes the packets inside the cluster, or (if the destination is outside the cluster) forwards them to a gateway node to be delivered to the other clusters.

By replacing the nodes with clusters, existing routing protocols can be directly applied to the network. Only gateways and clusterheads participate in the propagation of routing control/update messages. In dense networks this significantly reduces the routing overhead, thus solving scalability problems for routing algorithms in large ad hoc networks.

Several dynamic clustering strategies based on these ideas have been proposed in the literature, e.g., [13,56,113]. These strategies mainly differ in the criteria used to organize and maintain the cluster.

Clusterheads act as local coordinators, and in addition to support packets routing and forwarding, they may resolve channel scheduling, perform power measurement/control, maintain time division frame synchronization, [113,161]. For example, CDMA/TDMA techniques can be applied inside ad hoc networks by assigning a different code to each cluster, and using inside each cluster a TDMA scheduler managed by the clusterhead [113].

A clusterhead concentrates the traffic of a cluster, and as a consequence it may become a cluster bottleneck. This problem can be avoided by eliminating the clusterhead role, and adopting a fully distributed clustering approach, see e.g., [154,161].

A key point in the use of clustering techniques in a mobile environment is the maintenance of the network topology (i.e., nodes grouping, and identification of clusterheads, and gateways, if necessary) in the presence of various network events (mainly, the nodes' mobility). The clustering strategies proposed in the literature, generally apply static criteria for the implementation of clustering algorithms without taking directly into consideration the node mobility. Node mobility is a critical point because the membership of a node to a cluster changes over time due to the node mobility. Rearrangement of clusters may introduce excessive overheads that may nullify clustering benefits. To cope with the mobility problem, in [199] the node mobility is directly included inside the (α, t)-Cluster clustering algorithm. The objective of (α, t)-Cluster is to create and maintain a topology that adapts to node mobility. Specifically, (α, t)-Cluster partitions the network into clusters that provide some guarantees on the path stability with respect to nodes mobility. In detail, the nodes belonging to a cluster are expected to be reachable along paths internal to the cluster, and these paths have a lower-bounded availability, i.e., they are expected to be available for a period of time t, with a probability $\geqslant \alpha$ [199]. Intra-cluster routing can be implemented with proactive algorithms, while inter-cluster routing is based on a on-demand protocol.

5.3. TCP issues

TCP is an effective connection-oriented transport control protocol that provides the essential flow control and congestion control required to ensure reliable packet delivery [234]. TCP was originally designed to work in fixed networks. Because error rate in wired network is quite low, TCP uses packet loss as an indication for network congestion, and deals with this effectively by making corresponding transmission adjustment to its congestion window. Numerous enhancements and optimizations have been proposed over the past few years to improve TCP performance for infrastructure-based WLANs, and cellular networking environments, see e.g., [20,44,46,47]. The issues and solutions for using TCP over mobile networks are surveyed in [119]. Refs. [5,6] propose and evaluate solutions, based on the indirect TCP model, for the joint optimization of TCP performance and power saving in Wi-Fi hot spots.

Infrastructure-based wireless networks are 1-hop wireless networks where a mobile device uses the wireless medium to access the fixed infrastructure (e.g., the access point). Although there are a number of differences between infrastructure and ad hoc networks, many of these proposed solutions can be exploited also in the mobile ad hoc networks. For example, avoiding the invocation of congestion control mechanisms during packet losses by simply re-transmitting the lost packets. In addition, the mobile multi-hop ad hoc environment brings fresh challenges to TCP protocol. The dynamic topologies, and the interaction of MAC protocol mechanisms (e.g., 802.11 exponential back-off scheme) with TCP mechanisms (congestion control and time-out) lead in a multi-hop environment to new and unexpected phenomena. A survey on TCP research in MANET can be found in [4]. Hereafter, we summarize the main research areas, and the open issues.

Impact of mobility. In a MANET, nodes' mobility may have a severe impact on the performance of the TCP protocol [2,80,127,128,261]. Mobility may cause route failures, and hence, packet losses and increased delays. The TCP misinterprets these losses as congestion, and invokes the congestion control mechanism, potentially leading to unnecessary transmissions (during routes' reconstruction), and throughput degradation [71,127]. In addition, the stations' mobility may exacerbate the unfairness between competitive TCP sessions [261]. The performance of the TCP protocol when running (among others) over DSR and AODV are analyzed in [2,80,127,128]. These results point out the route failure frequency as an important factor in determining TCP throughput in ad hoc networks.

Nodes' Interaction at MAC Layer. Even when stations are static, the performance of an ad hoc network may be quite far from ideal, as the performances are strongly limited by the interaction between neighboring stations. A station activity is limited by the activity of neighboring stations inside the same TX_Range, IF_Range or PCS_Range, and by the interference caused by hidden and exposed stations. For example, in a chain topology stations early in the chain may cause starvation of later stations. Similar considerations apply to other network topologies. In general, the 802.11 MAC protocol appears to be more efficient in case of local traffic patterns, i.e., when the destination is close to the sender [28].

Impact of TCP congestion window size. TCP congestion window size may have a significant impact on performance. In [101], the authors show that, for a given network topology and traffic patterns, there exists an optimal value of the TCP congestion window size at which channel utilization is maximized. However, TCP does not operate around this optimal point, but typically with a window that is much larger, leading to decreased throughput (10–30% throughput degradation), and increased packet loss. These losses are due to link-layer drops: a station fails to reach its adjacent station due to the contention/interference of other stations. By increasing the congestion window size, the number of packets in the pipe between the sender and the receiver is increased, and hence the contention at the link-level increases, as well. Small congestion windows (i.e., 1–3 packets) typically provide the best performance [285,286].

Interaction between MAC protocol and TCP. The interaction of the 802.11 MAC protocol with the TCP protocol mechanisms may lead to unexpected phenomena in a multi-hop environment. For example, in the case of simultaneous TCP flows, severe unfairness problems and—in extreme cases—capture of the channel by few flows may occur. Furthermore, instantaneous TCP throughput may be very unstable also with a single TCP connection. These phenomena can be reduced/exacerbated by using small/large TCP-congestion window. These problems have been revealed in [285,286]. Recently, similar phenomena have been also observed in other scenarios [148]. Such phenomena do not appear, or appear with less intensity, when the UDP protocol is used [282].

Numerous new mechanisms for TCP optimization have also been proposed with the aim of resolving MANET specific issues, including adaptation of TCP error-detection and recovery strategies to the ad hoc environment. To minimize the impact of mobility and link disconnection on TCP performance, [71] proposed to introduce explicit signaling (Route Failure and Route Reestablishment notifications) from intermediate nodes to notify the sender TCP of the disruption of the current route, and construction of a new one. In this way, TCP after a link failure does not activates the congestion avoidance mechanisms, but simply freezes its status that will be resumed when a new route is found. In [127,128] an Explicit Link Failure Notification (ELFN) mechanism is introduced. The ELFN objective is to provide (through ELFN messages) the TCP at the sender-side explicit indications about link and route failures. In this case there is no explicit signaling about route reconstruction. Ref. [196] presents a simulation study of ELFN mechanism, both in static and dynamic scenarios. This study points out limitations of this approach that are intrinsic to TCP properties (e.g., long recovery time after a timeout), and proposes to implement mechanisms below the TCP layer. This is also the approach proposed and implemented in [172]. In this work, the standard TCP is unmodified, while new mechanisms are implemented in a new thin layer, ad hoc TCP (ATCP), between TCP and IP. This layer uses ECN messages and ICMP "destination unreachable" packets to distinguish congestion conditions from link failures, and from losses on the wireless links. According to type of event, ATCP takes the appropriate actions. Previous techniques require explicit notification by intermediate nodes to the sender. To avoid this complexity, [281] proposes to infer at the TCP level route changes by observing the out-of-order delivery events that are frequently introduced by a route change.

In [101], the authors focus on static multi-hop networks and provide a solution to fix TCP performance problems caused by MAC–TCP interactions (nodes' interaction at MAC layer plus TCP congestion window size). The basic observation here is that in multi-hop networks the channel utilization is associated to the spatial channel reuse. Spatial reuse defines, given network topology, nodes that may concurrently transmit without interfering with each other. For a given flow and network topology, there exists a contention-window that achieves the best channel reuse, thus providing the maximum throughput. However, legacy TCP operates with a window larger then the optimal one, and hence with a reduced throughput. To address this problem, two link level mechanisms have been proposed [101]: Link RED and adaptive spacing. Similarly to the RED mechanism implemented in Internet routers, the Link RED tunes the drop probability at the link level by marking/discarding packet according to the average number of retries experienced in the transmission of previous packets. The Link RED thus provides TCP with an early sign of overload at link level. Adaptive spacing is introduced to improve spatial channel reuse, thus reducing the risk of stations' starvation. The idea here is the introduction of extra backoff intervals to mitigate the exposed receiver problems. Adaptive spacing is complementary to Link RED: it is activated only when the average number of retries experienced in previous transmission is below a given threshold.

6. Applications and middleware

While the early MANET applications and deployments have been military oriented, non-military applications have also grown substantially since then. Especially in the past few years, with the rapid advances in mobile ad hoc networking research, mobile ad hoc networks have attracted considerable attention and interests from commercial business industry, as well as the standards community. The introduction of new technologies such as the Bluetooth, IEEE 802.11 and Hyperlan greatly facilitates the deployment of ad hoc technology outside of the military domain, and new ad hoc networking applications appeared mainly in specialized fields such as emergency services, disaster recovery and environment monitoring. In addition, MANET flexibility makes this technology attractive for several applicative scenarios like, for example, in personal area networking, home networking, law enforcement operation, search-and-rescue operations, commercial and educational applications, sensor networks [115]. Table 2 provides a categorization of present and possible future applicative scenarios for MANETs, as well as the services they may provide in each area.

6.1. Middleware

The middleware layer operates between the networking layers and the distributed applications (i.e., it mainly implements layers 5–7 of the OSI model), with the aim to build on top of raw network services, higher level mechanisms that easy the development and deployment of applications.

Mobile ad hoc systems currently developed adopt the approach of not having a middleware, but rather rely on each application to handle all the services it needs. This constitutes a major complexity/inefficiency in the development of MANET applications.

Research on middleware for mobile ad hoc networks is still in its infancy. Ad hoc networking and self-organization have not yet received the attention they deserve. Existing middleware mainly focus on mobile/nomadic environments, where a fixed infrastructure contains the relevant information. For an overview on middleware for mobile and pervasive systems, see [9,54,183].

Recently, in research circles, some middleware proposals for mobile ad hoc environments appeared in [116,180,184,195]. Their emphasis is on supporting transient data sharing [195] between nodes in communication range, data replication for disconnected operations [183], or both [116]. To achieve this, classical middleware technologies have been adopted. These include tuple space, mobile agents, and reactive programming through the usage of events' publishing/subscribing [9,183]. While these technologies provide service abstractions that highly simplify the application development, their efficiency in ad hoc environments is still an open issue. Specifically, among others, solutions must be devised to implement and manage in an efficient way agents' synchronization, shared memory, and to support group communications in an ad hoc network.

Among middleware services, *Service discovery and location* play a relevant role in ad hoc environments. Upon joining a self-organizing network, mobile nodes should be able to explore the environment to learn and locate the available services. Due to the scarce resources of a MANET the service discovery, and location should be designed to act in a "context aware" manner [183]. Context

Table 2
MANET applications

Applications	Descriptions/services
Tactical Networks	• Military communication, operations • Automated Battlefields
Sensor Networks [12]	• Home applications: smart sensor nodes and actuators can be buried in Appliances to allow end users to manage home devices locally and remotely • Environmental applications include tracking the movements of animals (e.g., birds and insects), chemical/biological detection, precision agriculture, etc. • Tracking data highly correlated in time and space, e.g., remote sensors for weather, earth activities
Emergency Services	• Search and rescue operations, as well as disaster recovery; e.g., early retrieval and transmission of patient data (record, status, diagnosis) from/to the hospital • Replacement of a fixed infrastructure in case of earthquakes, hurricanes, fire etc.
Commercial Environments	• E-Commerce: e.g., Electronic payments from anywhere (i.e., taxi) • Business: ○ dynamic access to customer files stored in a central location on the fly ○ provide consistent databases for all agents ○ mobile office • Vehicular Services: ○ transmission of news, road condition, weather, music ○ local ad hoc network with nearby vehicles for road/accident guidance
Home and Enterprise Networking	• Home/Office Wireless Networking (WLAN) e.g., shared whiteboard application; use PDA to print anywhere; trade shows • Personal Area Network (PAN)
Educational applications	• Setup virtual classrooms or conference rooms • Setup ad hoc communication during conferences, meetings, or lectures
Entertainment	• Multi-user games • Robotic pets • Outdoor Internet access
Location aware services	• Follow-on services, e.g., automatic call-forwarding, transmission of the actual workspace to the current location • Information services ○ push, e.g., advertise location specific service, like gas stations ○ pull, e.g., location dependent travel guide; services (printer, fax, phone, server, gas stations) availability information

information, such as node's current position (both geographical and logical in terms of network topology), neighborhood, available resources and constraints must be used to select the most appropriate service providers. A novel notion of "nearness" based on communication proximity (e.g., to measure the existence a stable communication path between the terminal and the service provider, rather then physical proximity) would be useful to estimate the amount of resources needed to access a service [267].

An approach to QoS-Aware resource discovery in ad hoc network has been presented in [176]. The proposed approach implements, in an ad hoc environment, the rendezvous discovery approach commonly used by middleware for mobile/nomadic networks, e.g., the Java Intelligent Network Infrastructure (Jini). Rendezvous servers (brokers) store the service-publish requests coming from service providers, and deliver service information to requesting clients. In an ad hoc network, brokers must be dynamically identified. Specifically, in [176] the brokers (directory agents) election happens through the usage of clusters formation techniques. To reduce the communication overheads, most of the discovery messages are only exchanged among these directory agents. Hash indexing is applied to distributed agents for reducing the query latency. Specifically, a hash function applied to the service attributes returns the list of directory agents. QoS guarantees are achieved through a continuous monitoring.

7. Cross layers' research issues

As we pointed out in Section 3 (see Fig. 2), there are research areas that may affect all layers of an ad hoc system. These include among others energy conservation, security and cooperation, simulation and performance evaluation, and QoS, presented in this section.

7.1. Energy conservation

Mobile devices rely on batteries for energy. Battery power is finite, and represents one of the greatest constraints in designing algorithms for mobile devices [100,137,175]. Projections on progress in battery technology show that only small improvements in the battery capacity are expected in next future [238]. Under these conditions, it is vital that power utilization be managed efficiently by identifying ways to use less power, preferably with no impact on the applications. Limitation on battery life, and the additional energy requirements for supporting network operations (e.g., routing) inside each node, make the energy conservation one of the main concern in ad hoc networking [53]. The importance of this problem has produced a great deal of research on energy saving in wireless networks in general [219], and ad hoc networks in particular [52,58]. Strategies for power saving have been investigated at several levels of a mobile device including the physical-layer transmissions, the operating system, and the applications [143]. Ref. [70] points out battery properties that impact on the design of battery powered devices.

Power-saving policies at the operating system level include strategies for CPU scheduling [174,279], and for the hard-disk management [122]. At the application-level, policies that exploit the application semantic or profit of tasks remote execution have been proposed [143]. However, in small mobile devices, networking activities have a major impact on energy consumption. Experimental results show that power consumption related to networking activities is approximately 10% of the overall power consumption of a laptop computer, but it raises up to 50% in handheld devices [149]. The impact of network technologies on power consumption has been investigated in depth in [243]. The key point in energy-aware networking is the fact that a wireless interface consumes nearly the same amount of energy in the receive, transmit, and idle state; while in the sleep state, an interface cannot transmit or receive, and its power consumption is highly reduced. For example, measurements of 802.11 "Wi-Fi" wireless interfaces [61,86,98,225] show that the ratio between power consumption in the transmit and idle state is less than two (the receiving state being intermediate); furthermore, the idle-state power consumption is about one order of magnitude greater than that in the sleep state. Hence, to reduce energy consumption of a network interface, it is necessary to define network protocols that maximize the time the interface spends in a power saving mode (e.g., the sleep state) by eliminating/reducing the network interface idle times. This approach has been extensively applied in infrastructure-based wireless networks where effective policies have been defined at all layers of the protocol stack by moving the communication and computation efforts on the fixed infrastructure, and maintaining the network interface of the mobile device in the sleep state for most of the time, see e.g., [8] and references herein. This is not a viable approach in an ad hoc network however, where such fixed elements generally do not exist. In addition, self-organization introduces a new metric for measuring the energy savings: the network lifetime. In an infrastructure wireless network, energy management strategies are local to each node, and are aimed to minimize the node energy consumption. This metric is not viable for ad hoc networks where nodes must also cooperate to network operations to guarantee 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 lifetime of the network.

We can, therefore, identify (at least) two classes of power-saving strategies for ad hoc networks: *local strategies*, that typically operate on small time scales (say milliseconds), and *global strategies* that operate on longer time scales.

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 typically operate at the physical and MAC layer, with the aim to maximizing the node battery lifetime without affecting the behavior of the high-level protocols. By focusing on power saving at the transmission level, some authors have proposed and analyzed policies (based on monitoring the transmission error rates), which avoid useless transmissions when the channel noise makes low the probability of a successful transmission [224,297]. Similar policies have been proposed for random access-based MAC protocols [24,26]. Specifically, at the MAC layer, power-saving strategies are designed to avoid transmitting when the channel is congested, and hence there is a high collision probability. These policies achieve power consumption by reducing the energy required to successfully transmit a packet. By applying these policies to the IEEE 802.11 MAC protocol, in [26] it has been shown that optimal tuning of the network interface for achieving the minimal energy consumption almost coincides with the optimal channel utilization. This behavior is associated with the energy consumption model of WLANs interface in which the receive, transmit, and idle states are almost equivalent from a power consumption standpoint.

In general, power saving in CSMA-based protocols is achieved by using the information derived from the media access control protocol to find intervals during which the network interface does not need to be listening. For example, while a node transmits a packet, the other nodes within the same interference and carrier-sensing range must remain silent. Therefore, these nodes can sleep with little or no impact on system behavior. For example, PAMAS [231] turns off a node's radio when it is overhearing a packet not addressed to it. Ref. [73] presents a comparison of a number of MAC-layer protocols from the energy efficiency standpoint. In [69] the authors consider low-cost large-scale devices and present a new approach to energy-efficient MAC protocols based on a pseudo-random protocol, which combines the fairness from random access protocols with the low energy requirements of classical TDMA.

The IEEE 802.11 standard includes a power saving mechanism effective for one-hop ad hoc networks. This scheme maintains synchronization among nodes that therefore can wake up at the same set of time instants, exchange traffic and other management information, and then return to a sleeping state. Additional details on the 802.11 power saving mechanism can be found in [92], while [89,270] analyze its effectiveness. The 802.11 approach is suitable for static single-hop networks in which nodes' synchronization can be achieved with a limited effort. This requirement is not feasible in dynamic multi-hop ad hoc networks.

Global strategies. The aim of global strategies is to maximize the network lifetime. These are based a network-wide approach to power saving, and on the idea that when a region is dense in terms of nodes, only a small number of them need to be turned on in order to forward the traffic. To achieve this a set of nodes is identified which must guarantee network connectivity (to participate in packets routing and forwarding), while remaining nodes can spend most of the time in the sleep state to maximize energy saving. Nodes participating in packet forwarding may naturally exhaust their energy sooner, thus compromising the network connectivity. Therefore, periodically, the set of active nodes is recomputed by selecting alternative paths in a way that maximizes the overall network lifetime. Identifying the network's dominating sets is a typical goal of a global strategy. A dominating set is a subset of network nodes such that each node is in the set, or it has a neighbor in that set. Dominating sets, if connected, constitute the routing/forwarding backbone in the ad hoc network. As the computation of the minimal dominating set is computationally unfeasible, in the literature several distributed algorithms exist to approximate suitable dominating sets, see for example [61,81,269, 272,283,284]. Span [61] is a distributed algorithm to construct dominating sets using nodes local decisions to sleep, or to join the routing backbone. Nodes participating in the backbone are named *coordinators*. Coordinators are always in an active state, while non-coordinator nodes are normally in the sleep state, and wake up to exchange traffic with the coordinators. Periodically, the coordinators' set is recomputed. The effectiveness of Span depends on the energy consumption in the idle and sleep state: Span benefit increases with the increase of the idle-to-sleep energy-consumption ratio [61]. Span integrates with the 802.11 power saving mode, thus guaranteeing that non-coordinator nodes can receive packets that are buffered by the coordinators while they are sleeping. Nodes physical position (obtained for example via GPS) is used in the GAF algorithm to construct the routing/forwarding backbone. A grid structure is superposed on the network, and each node is associated with a square in the grid using its physical position. Inside the square only one node is in the non-sleeping state [284]. AFECA [283] is an asynchronous distributed algorithm for constructing a routing backbone. Nodes alternate between active and sleep states, where in principle a node remains in the sleep state for a time proportional to the number of its neighbors, thus guaranteeing, in average, a constant number of active nodes.

Controlling the power of the transmitting node is the other main direction for achieving power saving in ad hoc networks. In addition, a reduced transmission power allows spatial reuse of frequencies, which can help increasing the total throughput of network and minimize interference.

In wireless systems, the existence or lack of a link between two nodes mainly depends (given the acceptable bit error rate) on the transmission power and the transmission rate. By increasing the transmission power the number of feasible links is increased, but at the same time this increases the energy consumption and the interference [85]. Recently, several studies focused on controlling network topology by assigning per-node transmit powers that guarantee network connectivity, and minimize the transmit power [92,202,222,230,273]. The algorithmic aspects of topology control problems are discussed in [167].

Transmission power is highly correlated with energy consumption. It determines both the amount of energy drained from the battery for each transmission, and the number of feasible links. These two effects have an opposite impact on the energy consumption. 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. On one hand, we have to consider the fact that signal strength at a distance r from the sender has non-linear decay, specifically $S(r) = S \cdot r^{-\alpha}$ $(\alpha \in [2, 4])$, where S is the amplitude of the transmitted signal [85]. This implies that covering the sender-to-receiver distance a multi-hop path may require less energy, from the transmission standpoint. On the other hand, on a multi-hop path the delay (due to the multiple hops), as well as the processing energy (to receive and locally process a packet) increase.

The trade-off between minimum transmission power and number of hops further complicates the design of routing algorithms. A large part of recent work on energy efficiency in ad hoc networks is concentrated on routing [227,230,245,255], where the transmitting power level is an additional variable in the routing protocol design [91]. This problem has been addresses from two different perspectives: (i) energy is an expensive, but not a limited resource (battery can be recharged/replaced), or (ii) the energy is finite. The former case applies to mobile ad hoc network in general, while the latter appears to be a suitable model for sensor networks. In case (i), energy consumption must be minimized; typically, this translates in the following target: *minimize the total energy consumed per packet to forward it from source to destination*. The minimization of per-packet energy does not maximize network lifetime, as residual energy of the nodes is not taken into consideration. On the other hand, in case (ii), the energy is a hard constraint [85], and the maximum lifetime is the target.

Minimum-energy routings minimize the energy consumed to forward a packet from the source to the destination [103,162,227]. Similarly to proactive routing algorithms [162,227] try to find minimum energy routes for all nodes, while PARO [103] behaves as a reactive algorithm by minimizing the energy consumption of ongoing flows. In PARO, nodes intermediate to the source–destination pair elect themselves to forward packets, thus reducing the aggregate transmission power consumed by network devices. PARO attempts to maximize the number of redirector nodes between source–destination pairs, thereby minimizing the transmission power.

On-line maximum-lifetime routing is a complex problem [157]. In [75], for a static network with known and constant flows, the maximum lifetime routing is modeled as a linear programming problem. The solution of this model provides the upper bound on the network lifetime that is used to analyze the effectiveness of the algorithms. For a single power level, an optimal algorithm is presented; while, for the general case, the authors present an algorithm that selects routes and adjusts the corresponding power levels achieving a close to the optimal lifetime.

A balance between minimum-energy and maximum lifetime is the target of the CMMBCR strategy [256]. CMMBCR applies a conditional strategy that uses the minimum energy route, if the nodes residual energy is greater than a given threshold. Otherwise, a route that maximizes the minimum residual energy is selected.

7.2. Network security and cooperation

Wireless mobile ad hoc nature of MANET brings new security challenge to the network design. Mobile wireless networks are generally more vulnerable to information and physical security threats than fixed wired networks. Vulnerability of channels and nodes, absence of infrastructure and dynamically changing topology, make ad hoc networks security a difficult task [35]. Broadcast wireless channels allow message eavesdropping and injection (vulnerability of channels). Nodes do not reside in physically protected places, and hence can easily fall under the attackers' control (node vulnerability). The absence of infrastructure makes the classical security solutions based on certification authorities and on-line servers inapplicable. Finally, the security of routing protocols in the MANET dynamic environment is an additional challenge.

The self-organizing environment introduces new security issues that are not addressed by the basic security services provided for infrastructure-based networks. Security mechanisms that solely enforce the correctness or integrity of network operations would thus not be sufficient in MANET. A basic requirement for keeping the network operational is to enforce ad hoc nodes' contribution to network operations, despite the conflicting tendency (motivated by the energy scarcity) of each node towards selfishness [114, 191].

7.2.1. Security attacks

Securing wireless ad hoc networks is a highly challenging issue. Understanding possible form of attacks is always the first step towards developing good security solutions. Ad hoc networks have to cope with the same kinds of vulnerabilities as their wired counterparts, as well as with new vulnerabilities specific to the ad hoc context [117]. Furthermore, traditional vulnerabilities are also accentuated by the ad hoc paradigm.

The complexity and diversity of the field (different applications have different security constraints) led to a multitude of proposals that cannot be all surveyed in this article. Detailed analyses of ad hoc networking security issues and solutions can be found in [35,129,193]. Below we summarize only the main directions of security in ad hoc networks.

Performing communication in free space exposes ad hoc networks to attacks as anyone can join the network, and eavesdrop or inject messages. Ad hoc networks attacks can be classified as passive or active [155]. Passive attack signifies that the attacker does not send any message, but just listens to the channel. A passive attacks does not disrupt the operation of a protocol, but only attempts to discover valuable information. During an active attack, on the other hand, information is inserted into the network.

Passive eavesdropping is a passive attack that attempts to discover nodes information (e.g., IP addresses, location of nodes, etc.) by listening to routing traffic. In a wireless environment it is usually impossible to detect this attack, as it does not produce any new traffic in the network.

Active attacks involve actions such as the replication, modification and deletion of exchanged data. Certain active attacks can be easily performed against an ad hoc network. These attacks can be grouped in [145]: Impersonation, Denial of service, and Disclosure attack.

Impersonation. In this type of attack, nodes may be able to join the network undetectably, or send false routing information, masquerading as some other trusted node. The Black Hole attack [83] falls in this category: here a malicious node uses the routing protocol to advertise itself as having the shortest path to the node whose packets it wants to intercept. A more subtle type of routing disruption is the creation of a tunnel (or Wormhole) in the network between two colluding malicious nodes [126]. Ref. [125] provides a detailed description of several attacks on routing.

Denial of service. The Routing Table Overflow and the Sleep Depravation attacks [236] fall in this category. In the former, the attacker attempts to create routes to non-existent nodes to overwhelm the routing-protocol implementations. In the latter, the attacker attempts to consume batteries of other nodes by requesting routes, or by forwarding unnecessary packets.

Disclosure attack. A location disclosure attack can reveal something about the physical location of nodes or the structure of the network. Two types of security mechanisms can generally be applied: preventive and detective. Preventive mechanisms are typically based on key-based cryptography. Keys distribution is therefore at the center of these mechanisms. Secret keys are distributed through a pre-established secure channel, and this makes symmetric cryptography generally difficult to apply in ad hoc networks. Public keys are distributed through certificates that bind a public key to a device. In the centralized approach, certificates are provided, stored, and distributed by the Certificate Authority. Since no central authority, no centralized trusted third party, and no central server are possible in MANET, the key management function needs to be distributed over nodes. In [294], the key management responsibility is shared among a set of nodes, called servers. The challenge of constructing such a trustworthy aggregation lies not only in how to create and configure the aggregation, but also in how the aggregation maintains its security by adapting to changes in the network topology. Ref. [49] presents a fully distributed self-organizing public key management system for MANETs. In this approach the users issue certificates for each other based on their personal acquaintances. Certificates are stored in a *local certificate repository* and distributed by the users themselves. When two users want to verify the public keys of each other, they merge their local certificate repositories.

In [117], the authors analyze the vulnerabilities of key-based security mechanisms, and propose solutions to protect these mechanisms.

The intrusion detection field studies how to discover that an intruder is attempting to penetrate the network to perform an attack. Most of the intrusion detection techniques developed on a fixed wired network are not applicable in this new environment. In ad hoc network there are no traffic concentration points (switches, routers, etc.) where the intrusion detection system (IDS) can collect audit data for the entire network. The only available audit trace will be limited to communication activities taking place within the radio range, and the intrusion detection algorithm must rely on this partial and localized information. A proposal for a new intrusion detection architecture that is both distributed and cooperative is presented in [295,296]. Here all nodes in the wireless ad hoc network participate in intrusion detection and reaction. Each node is responsible for detecting signs of intrusion locally and independently, but neighbors can collaboratively investigate in a broader range.

The Intrusion-Resistant Ad Hoc Routing Algorithms (TIARA) [223] is designed against denial of service attacks. The TIARA mechanisms limit the damage caused by intrusion attacks, and allow for continued network operations at an acceptable level during such attacks.

7.2.2. Security at data link layer

Bluetooth and 802.11 implement mechanisms based on cryptography to prevent unauthorized accesses, and to enhance the privacy on radio links. An analysis of the various 802.11 and Bluetooth mechanisms can be found in [193].

Security in the IEEE 802.11 standard is provided by the Wired Equivalent Privacy (WEP) scheme. WEP supports both data encryption and integrity. The security is based on a 40-bit secret key. The secret key can either be a default key shared by all the devices of a WLAN, or a pair-wise secret key shared only by two communicating devices. Since WEP does not provide any support for the exchange of pair-wise secret keys, the secret key must be manually installed on each device. As WEP suffers from various design flaws and weaknesses [193], to correct the WEP problems a task group part of the IEEE 802.11i standardization is designing the new 802.11 security architecture.

Bluetooth uses cryptographic security mechanisms implemented in the data link layer. A key management service provides each device with a set of symmetric cryptographic keys required for the initialization of a secret channel with another device, the execution of an authentication protocol, and the exchange of encrypted data on the secret channel. A detailed presentation of Bluetooth security mechanisms, together with an analysis of the weaknesses in the Bluetooth key management scheme can be found in [193].

7.2.3. Secure routing

Secure routing protocols cope with malicious nodes that can disrupt the correct functioning of a routing protocol by *modifying* routing information, by *fabricating* false routing information and by *impersonating* other nodes. Recent studies [216] brought up also a new type of attack that goes under the name of *wormhole* attack mentioned earlier.

We next summarize the recent research that has been done in order to come up with secure routing protocols for ad hoc networks. More details can be found in [88,193].

The Secure Routing Protocol [215] is conceived as an extension that can be applied to several existing *reactive* routing protocols. SRP is based on the assumption of the existence of a security association between the sender and the receiver based on a shared secret key negotiated at the connection setup. SRP combats attacks that disrupt the route discovery process. A node initiating a route discovery is able to identify and discard false routing information. Similarly to SRP, Ariadne [125] assumes that each pair of communicating nodes has two secret keys (one for each direction of the communication). Ariadne is a secure ad hoc routing protocol based on DSR and the TESLA authentication protocol [210].

The Authenticated Routing for Ad hoc Network (ARAN) protocol is an on-demand, secure, routing protocol that detects and protects against malicious actions carried out by third parties in the ad hoc environment [240]. ARAN is based on certificates, and assumes that nodes obtain certificates from a trusted certificate server before joining the ad hoc network. ARAN utilizes a route discovery procedure similar to AODV. To secure the communications, route discovery exploits an end-to-end authentication stage that guarantees that only the destination node can respond to a route discovery packet.

The Secure Efficient Ad hoc Distance (SEAD) is a *proactive* secure routing protocol based on DSDV. SEAD deals with attackers that *modify* a routing table update message. The basic idea is to authenticate the sequence number and the metric field of a routing table update message using one-way hash functions [120]. Hash chains and digital signatures are used by the SAODV mechanism to secure AODV [290].

7.2.4. Cooperation enforcing

A basic requirement for keeping an ad hoc network operational is to enforce ad hoc nodes' contribution to basic network functions such as packet forwarding and routing. Unlike networks using dedicated nodes to support basic network functions including packet forwarding, routing, and network management, in ad hoc networks those functions are carried out by all available nodes. This difference is at the core of some of the security problems that are specific to ad hoc networks. As opposed to dedicated nodes of a classical network, the nodes of an ad hoc network cannot be trusted for the correct execution of critical network functions. For example, routing is vulnerable in ad hoc networks because each device acts as a router. Forwarding mechanism is cooperative, as well. Communications between nodes, more than 1-hop away, are performed by exploiting intermediate relaying nodes. A node that does not cooperate is called a misbehaving node. Routing–forwarding misbehaviors can be caused by nodes that are malicious or selfish [191]. A malicious node does not cooperate because it wants to intentionally damage network functioning by dropping packets. On the other hand, a selfish node does not intend to directly damage other nodes, but is unwilling to spend battery life, CPU cycles, or available network bandwidth to forward packets not of direct interest to it, even though it expects others to forward packets on its behalf. Such a node uses the network but does not cooperate. To cope with these problems, a self-organizing network must be based on an incentive for users to collaborate, thus avoiding selfish behavior. There is a need for mechanisms that encourage/enforce users to behave as "good citizens", letting their device relay packets for the benefit of others, making their data available, and/or lending support to the other computations.

Most of the solutions, currently available in literature, present a similar approach to the cooperation problem [16,189,192]. They aim at detecting and isolating misbehaving nodes through a mechanism based on a watchdog and a reputation system. The watchdog identifies misbehaving nodes by performing neighborhood monitoring. This is done by promiscuously listening to the wireless link. According to collected information, the reputation system maintains a value for each observed node that represents the node's reputation. The reputation mechanism allows nodes of the network to isolate misbehaving nodes by not serving their requests. Existing solutions present advantages and disadvantages. The solution presented in [189] constitutes the starting point for research in this area. It extends the Dynamic Source Routing with a watchdog concept for the detection of non-forwarding nodes, and a "pathrater" for the avoidance of such nodes in routes. Every node in the network keeps ratings about every other node. The pathrater uses ratings to choose the network path that is most likely to deliver packets. The main drawback of such an approach is that it does not punish selfish nodes that therefore have no incentive to cooperate.

The CONFIDANT protocol [16] is an extension to the DSR intended to deal with the routing misbehavior problem. The objective is to make misbehavior unattractive by finding and isolating malicious nodes. Each node monitors the behavior of its one-hop neighbors. If a suspicious event is detected, this information is submitted to a reputation system, which maintains a list of ratings reflecting nodes' behavior. If the ratings become "intolerable", the information is given to a path manager which can deletes all routes containing the misbehaving node from the path cache. It can also decide to not serving routing/forwarding requests from a selfish host. A trust manager sends an alarm message to alert others of malicious nodes.

The CORE mechanism [192] copes with selfishness by stimulating node cooperation: nodes that want to use network resources have to contribute to routing and forwarding, thus balancing utilization and contribution to the network. Every node in the network monitors the behavior of its neighbors with respect to a requested function (packet forwarding, route discovery, etc.), and collects observations about the execution of that function. Based on the collected observations, each node computes a reputation value for each neighbor. When a neighbor's reputation falls below a predefined threshold, service provision to the misbehaving node is suspended. In this way, there is no advantage to node's misbehavior, as resource utilization will be suspended. Both CONFIDANT and CORE allow a type of "re-socialization" and reintegration of no longer (or wrongly accused) misbehaving nodes.

Some open issues can be identified in CONFIDANT and CORE approaches to cooperation. Firstly, the watchdog's weaknesses are not negligible: in presence of collisions, differences in the transmission ranges, or directional antennas, the watchdog is not able to properly monitoring the neighbors, and misbehaving nodes detection can fail. As these characteristics are quite frequent in ad hoc networks, watchdog observations can become meaningless. Another important aspect to consider is the employing of cooperation in security mechanisms. In the case of the CONFIDANT protocol, malicious nodes may initiate a new attack by sending false alarms about other nodes. The impact of wrong accusation spreading on the CONFIDANT reputation system is discussed in [17]. In the CORE mechanism no negative ratings are spread between nodes, but a malicious node can deceive the reputation system by sending forged Route Reply. Finally, both CONFIDANT and CORE do not take into account network utilization: by totally avoiding all routes containing misbehaving nodes, they create a risk of diverting all the traffic to well behaving nodes, with the result of overloading these and links between them. Optimizing network utilization, while avoiding misbehaving nodes is the target of the work presented in [59]. This paper presents a framework that confronts, in addition to malicious and selfish nodes, misbehavior caused by uncontrollable events. By exploiting reliability indices, certain packet forwarding policies are defined and contrasted to increase the network performance (i.e., optimize network utilization), and reliability (i.e., avoiding misbehaving nodes).

An original approach to cooperation is proposed in [36]. In this work an economic model is used to enforce cooperation. The solution presented in this paper consists of the introduction of a virtual currency, *nuglet* used in every network operation that requires nodes' cooperation. Specifically, it is assumed that every node has a tamper resistant security module, which maintains a nuglet counter. This counter is decremented (down to zero) when the node wants to send one of its own packets (i.e., the node has to pay for its own transmissions). On the other hand, the nuglet counter is increased (i.e., the node gets a reward) when the node forwards a packet for the benefit of other nodes.

A survey of cooperation mechanism is presented in [114] where the relationship between cooperation in ad hoc networks and people social behavior is presented. From this perspective, Game theory is a natural way for modeling and analyzing cooperation aspects in ad hoc networks. Game rules model the freedom of every node to choose cooperation or isolation. The use of game theory to model the cooperation in ad hoc network is presented in [194,266]. In the model presented in [266] nodes are players, communications are moves, and the repetition of the basic game throughout time models subsequent communications (mobility is taken into account by means of a discount factor that makes future uncertain in every moment). Authors show that cooperation can be fully enforced with local observation if mobility is low. Furthermore, they show that a node will forward at most the same amount of traffic it generates. In [194] both a cooperative game approach and a non-cooperative game approach, are applied to evaluate the effectiveness of the CORE mechanism.

7.3. Simulation and performance evaluation

There are two main approaches in system performance evaluation: the first uses measurements; the second is based on a representation of the system behavior via a model [150,156]. Measurement techniques are applied to real systems, and thus they can be applied only when a real system, or a prototype of it, is available. Currently, only few measurements studies on real ad hoc testbeds can be found in the literature, see e.g., [11,41]. The Uppsala University APE testbed [11] is one of the largest, having run tests with more than thirty nodes. The results from this testbed are very important as they are pointing out problems that were not detected by preceding simulation studies. An important problem, related to the different transmission ranges for 802.11b control and data frames, is the so-called *communication gray zones* problem [170]. This problem was revealed by a group of researchers at the Uppsala University, while measuring the performance of their own implementation of the AODV routing protocol in an IEEE 802.11b ad hoc network. Observing an unexpected large amount of packets' losses, mainly during route changes, it was found that increase in packet loss occurred in some specific geographic areas termed called "*communication gray zones*". In such zones, the packet loss experienced by a station may be extremely high, up to 100%, thus severely affecting the performance of applications associated with a continuous packet flow (e.g., file transfers and multimedia streaming). It was also found that the reason for this phenomenon is that a station inside a gray zone is considered (using the routing information) reachable by a neighboring station, while actual data communication between the stations is not possible. The same problem was found to affect other routing protocols, such as OLSR. It is important to point out that communication gray zone problem cannot be revealed by commonly used simulation tools (e.g., NS-2, Glomosim), as in these 802.11 models both unicast and broadcast transmissions are performed at 2 Mbps, and hence have the same transmission range.

Constructing a real ad hoc network testbed for a given scenario is typically expensive and remains limited in terms of working scenarios, mobility models, etc. Furthermore, measurements are generally non-repeatable. For these reasons, protocols scalability, sensitiveness to users mobility patterns and speeds are difficult to investigate on a real testbed. Using a simulation or analytic model, on the other hand, permits the study of system behavior by varying all its parameters, and considering a large spectrum of network scenarios.

Evaluating system performance via a model consists of two steps: (i) defining the system model, and (ii) solving the model using analytical and/or simulative techniques. Analytical methods are often not detailed enough for the ad hoc networks evaluation and in terms of accounting for mobility, in their infancy. On the other hand, simulation modeling is a more standardized, mature, and flexible tool for modeling various protocols and network scenarios, and allows (by running the simulation model) collection and analyses that fully characterize the protocol performance in most cases.

A very large number of simulation models have been developed to study ad hoc network architectures and protocols under many network scenarios (number of nodes, mobility rates, etc.). Simulation studies have been extensively applied for instance to compare and contrast large number of routing protocols developed for MANETs, see e.g., [42,82,84,140]. Ref. [99] presents a theoretical framework to compare ad hoc-network routing protocols (in an implementation independent manner) by measuring each protocol's performance relative to a theoretical optimum.

The use of simulation techniques in the performance evaluation of communication networks is a consolidated research area (see [55] and the references herein), however MANET simulation has several open research issues. An in depth discussion of methods and techniques for MANETs simulation can be found in [19]. In the following, we discuss two current topics: (i) models of nodes mobility and (ii) network simulators.

7.3.1. Mobility models

The ability of ad hoc networks' protocols to correctly behave in a dynamic environment, where devices position may continuously change, is a key issue. Therefore, modeling users' movements is an important aspect in ad hoc network simulation. This includes among others [19]:

- the definition of the simulated area in which users movements take place, and the rules for modeling users that moves beyond the simulated area;
- the number of nodes in the simulated area, and the allocation of nodes at the simulation start up; and
- the mobility model, itself.

Typically, simulation studies assume a number of users that moves inside a closed rectangular area. Closed here stands for a constant number of users inside the simulated area. Rules are defined for users arriving at the edges of the area. For example, in [127] the network model consists of 30 nodes in a 1500 m $\times$ 300 m closed rectangular area.

The random waypoint mobility model is the model most commonly used to define the way users move in the simulated area. According to this model, nodes move according to a broken line pattern, standing at each vertex for a model-defined pause time (p). Specifically, each node picks a random destination in the rectangular area, sample a speed value according to a uniform distribution in the range $(0, v_{\max}]$, and then travels to the destination along a straight line. Once the node arrives at its destination, it pauses for a time p, then chooses (draws) another destination and continues onward. The pause time and the maximum speed, v, are mobility parameters. By changing these values various system mobility patterns are captured. For example, $p = 0$ signifies that all nodes are always in motion throughout the simulation run.

Recent studies have pointed out problems in the random waypoint model. Two specific types of problems have been identified: (i) the nodes average speed is decreasing, and (ii) the nodes' distribution in the simulated area is non-uniform.

Average Speed. The random waypoint model is expected to guarantee an average speed of $v_{max}/2$ throughout the simulation run. On the other hand, results presented in [288] show that the average node speed decreases over time: while the simulation progress, more and more nodes are involved in traveling long distance at low speeds. This behavior of the random waypoint model generates invalid results. The simulation experiments never enter a steady state, and the time-averaged statistics drastically change over time. A simple solution based on avoiding speeds close to zero is suggested in [288] to overcome this problem. By sampling the speed in the range $[1, v_{max} - 1]$, after a transient period, the simulation enters a steady state in which the average speed is, as expected, equal to $v_{max}/2$.

Nodes' Distribution. Nodes moving according to the random waypoint model tend to concentrate in the middle of the simulated area, creating the so-called border effect [14,15,37]. This yields node spatial distribution that is not uniform. In [45], it is shown that for large values of the pause time the border effect is limited, and the spatial distribution can well approximate uniform distribution. However, for other mobility parameters, the border effect may become highly pronounced, and the assumption of the uniform distribution of the nodes in the simulated area is no longer valid.

7.3.2. Network simulators

Most MANET simulative studies are based on simulation tools. The main advantage of these tools is that they provide libraries containing predefined models for most communication protocols (e.g., 802.11, Ethernet, TCP, etc.). In addition, these tools often provide graphical interfaces that can be used both during the model development phase, and during simulation runs to simplify following dynamic protocol and network behaviors.

Popular network simulators used in ad hoc networks include: OPNET [204], NS-2 [200], Glomosim [109] and its commercial version QualNet [220]. They all provide advanced simulation environments to test and debug different networking protocols, including collision detection modules, radio propagation and MAC protocols. Some recent results question however the validity of simulations based on these tools. Specifically, [74] presents the simulative results of the flooding algorithm using OPNET, NS-2 and Glomosim. Important divergences between the simulators results have been measured. The observed differences are not only quantitative (not the same absolute value), but also qualitative (not the same general behavior) making some past observation of MANET simulation studies an open issue.

7.4. Quality of service

Providing Quality of Service (QoS), other than best effort, is a very complex problem in MANETs, and makes this area a challenging area of future MANET research [181]. Network's ability to provide QoS depends on the intrinsic characteristics of all the network components, from transmission links to the MAC and network layers [232]. MANET characteristics generally lead to the conclusion that this type of network provides a weak support to QoS. Wireless links have a (relatively) low and highly variable capacity, and high loss rates. Topologies are highly dynamic with frequent links breakages. Random access-based MAC protocols, which are commonly used in this environment (e.g., 802.11b), have no QoS support. Finally, MANET link layers typically run in unlicensed spectrum, making it more difficult to provide strong QoS guarantees in spectrum hard to control [181]. This scenario indicates that, not only hard QoS guarantees will be difficult to achieve in a MANET, but if the nodes are *highly mobile* even statistical QoS guarantees may be impossible to attain, due to the lack of sufficiently accurate knowledge (both instantaneous and predictive) of the network states [38]. Furthermore, since the quality of the network (in terms of available resources reside in the wireless medium and in the mobile nodes: e.g., buffer and battery state) varies with time, present QoS models for wired networks are insufficient in a self-organizing network, and new MANET QoS model must be defined [118]. Specifically, DiffServ and IntServ (i.e., the Internet QoS models) require accurate link state (e.g., available bandwidth, packet loss rate delay, etc.) and topology information. In [118,287], an attempt is made to define a MANET QoS model that benefits from the concepts and features of the existing models. The Flexible QoS Model for MANET (FQMM) is based both on IntServ and Diffserv. Specifically, for applications with high priority, per-flow QoS guarantees of IntServ are provided. On the other hand, applications with lower priorities achieve DiffServ per-class differentiation. As FQMM separately applies both IntServ and DiffServ for different priorities, the drawbacks related to IntServ and DiffServ still remain. A more realistic direction for QoS provisioning in ad hoc network is based on an adaptive QoS model: applications must adapt to the time-varying resources offered by the network. In [201], the QoS model for a MANET is defined as *providing a set of parameters in order to adapt the application to the "quality" of the network*.

The quality of service provided by the network is not related to any dedicated network layer rather it requires coordinated efforts from all layers. Important QoS components include: QoS MAC, QoS routing, and resource-reservation signaling [214,271].

QoS MAC protocols solve the problems of medium contention, support reliable unicast communications, and provide resource reservation for real-time traffic in a distributed wireless environment [271]. Among numerous MAC protocols and improvements that have been proposed, protocols that can provide QoS guarantees to real-time traffic in a distributed wireless environment include GAMA/PR protocol [188] and Black-Burst (BB) contention mechanism [244].

QoS routing refers to the discovery and maintenance of routes that can satisfy QoS objectives under given resource constraints, while QoS signaling is responsible for actual admission control, scheduling, as well as resource reservation along the route determined by QoS routing, or other routing protocols. Both QoS routing and QoS signaling coordinate with the QoS MAC protocol to deliver the required QoS.

Much research has been done in each of these component areas [64,168,214,271]. INSIGNIA is the first QoS signaling protocol specifically designed for resource reservation in ad hoc environments [7,159]. It supports in-band signaling by adding a new option field in IP header called INSIGNIA to carry the signaling control information. Like RSVP, the service granularity supported by INSIGNIA is per-flow management. The INSIGNIA module is responsible for establishing, restoring, adapting, and tearing down real-time flows. It includes fast flow reservation, restoration and adaptation algorithms that are specifically designed to deliver adaptive real-time service in MANETs [159]. If the required resource is unavailable, the flow will be degraded to best-effort service. QoS reports are sent to source node periodically to report network topology changes, as well as QoS statistics (loss rate, delay, and throughput). DRSVP [197] is another QoS signaling protocols for MANET based on RSVP.

QoS routing helps establishing the route for successful resource reservation by QoS signaling [66,271]. This is a difficult task. In order to make optimal routing decision, QoS routing requires constant updates on link state information such as delay, bandwidth, cost, loss rate, and error rate to make policy decision, resulting in large amount of control overhead, which can be prohibitive for bandwidth constrained ad hoc environments. In addition, the dynamic nature of MANETs makes maintaining the precise link state information extremely difficult, if not impossible [38,239,271]. Finally, even after resource reservation, QoS still cannot be guaranteed due to the frequent disconnections and topology changes. Several QoS routing algorithms were published recently with a variety of QoS requirements and resource constraints [66,214], for example, CEDAR [249], ticket-based probing [68], Predictive Location-Based QoS Routing [250], Localized QoS routing

[289], and QoS routing based on bandwidth calculation [166].

8. Discussion and conclusions

In coming years, mobile computing will keep flourishing, and an eventual seamless integration of MANET with other wireless networks, and the fixed Internet infrastructure, appears inevitable. Ad hoc networking is at the center of the evolution towards the 4th generation wireless technology. Its intrinsic flexibility, ease of maintenance, lack of required infrastructure, auto-configuration, self-administration capabilities, and significant costs advantages make it a prime candidate for becoming the stalwart technology for personal pervasive communication. The opportunity and importance of ad hoc networks is being increasingly recognized by both the research and industry community, as evidenced by the flood of research activities, as well as the almost exponential growth in the Wireless LANs and Bluetooth sectors.

In moving forward towards fulfilling this opportunity, the successful addressing of open technical and economical issues will play a critical role in achieving the eventual success and potential of MANET technology. From the technical standpoint, as shown in this article, despite the large volume of research activities and rapid progress made in the MANET technologies in the past few years, almost all research areas (from enabling technologies to applications) still harbor many open issues. This is characteristically exemplified by research activities performed on routing protocols. Most work on routing protocols is being performed in the framework of the IETF MANET working group, where four routing protocols are currently under active development. These include two reactive routing protocols, AODV and DSR, and two proactive routing protocols, OLSR and TBRPF. There has been good progress in studying the protocols' behavior (almost exclusively by simulation), as can be seen in the large conference literature in this area, but the absence of performance data in non-trivial network configurations continues to be a major problem. The perception is that of a large number of competing routing protocols, a lack of WG-wide consensus, and few signs of convergence [178]. To overcome this situation, a discussion is currently ongoing to focalize the activities of the MANET WG towards the design of IETF MANET standard protocol(s), and to split off related long-term research work from IETF. The long-term research work may potentially move to the IETF's sister organization, the IRTF (Internet Research Task Force) that has recently established a group on "Ad hoc Network Scaling Research".

MANET WG proposes a view of mobile ad hoc networks as an evolution of the Internet. This mainly implies an IP-centric view of the network, and the use of a layered architecture. Current research points out though that this choice may limit developing efficient solutions for MANET. Other promising directions have been identified [115]. The use of the IP protocol has two main advantages: it simplifies MANET interconnection to the Internet, and guarantees the independence from wireless technologies. On the other hand, more efficient and lightweight solutions can be obtained, for example, by implementing routing solutions at lower layers [10,259]. Furthermore, masking lower layers' characteristics may not to be useful in MANET. The layered paradigm has highly simplified Internet design, however when applied to ad hoc networks, it may result in poor performance as it prevents exploiting important inter-layer dependencies in designing efficient ad hoc network functions. For example, from the energy management standpoint, power control and multiple antennas at the link layer are coupled with power control and scheduling at MAC layer, and with energy-constrained and delay-constrained routing at network layer [115]. Relaxing the Internet layered architecture, by removing the strict layer boundaries, is an open issue in the MANET evolution. Cross-layer design of MANET architecture and protocols is a promising direction for meeting the emerging application requirements, particularly when energy is a limited resource.

From the economic standpoint, the main question to be addressed in the MANET model is the identification of business scenarios that can move MANET's success beyond the academy and research labs. Currently, apart from specialized areas (battlefield, disaster recovery, etc.), the main business opportunity appears to be in tools (see, e.g., MeshNetworks [5] and SPANworks [6]), which let PDAs and/or laptops, set up "self-organizing networks". However, no clear understanding of a MANET "killer application(s)" has yet emerged. Legacy, content-orientated services and applications enhanced by the self-organizing paradigm could become such an application, as similar to SMS, it would allow to exploit the mobility provided by cellular systems. Users' benefits gained with the use of the ad hoc technology could make the difference compared to legacy applications (shared whiteboard, chat, file-sharing). Part of bringing the MANET technology to the users is the development of large testbeds with direct users' involvement, as in [190].

In addition to the development of applications and system solutions tailored to the ad hoc paradigm, MANET may offer business opportunities for network service provider, and potentially open the wireless arena to new operators. The lack of infrastructure in MANET is appealing to new commercial systems since it circumvents the need for a large investment to get the network up and running, and the development costs may be scales with network success [115]. Minimum investments, coupled with the emerging tendency (mainly in USA) to deregulate the spectrum environment to create a secondary market, eliminate/reduce the barriers to new operators entering the market to offer new wireless services. However, the MANET potentialities cannot become a reality without an economic model that identifies potential revenues behind MANET-based network services. For example, network services based on the MANET paradigm could be used to efficiently extend the capacity/coverage of Wi-Fi hot spots. It is expected that the bandwidth request in hot spots will increase rapidly, thus requiring higher speed access technologies. With the current 802.11 technology, higher speeds imply a reduction in the coverage area of the Access Point (AP). Spreading in a hot spot a large number of APs to guarantee the coverage is not appealing both from the economic (infrastructure cost) and technical standpoint (APs interference). The ad hoc paradigm can possibly offer an efficient solution to this problem: the APs upgraded with multi-rate high-speed technologies (e.g., 802.11a) achieve the required coverage by exploiting a multi-hop wireless network. While from a technology standpoint, feasible solutions can be designed to apply the MANET technology to extend APs' coverage; the critical point remains the economic model. Which model could be applied for example in such a scenario to have users cooperating to provide support to the network-service provisioning remains a question that typifies the open issues on the way of transitioning MANET results into the business environment.

[5] http://www.meshnetworks.com

[6] http://www.spanworks.com

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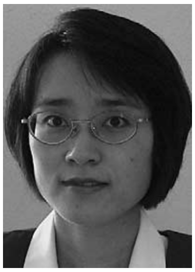

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