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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.

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 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, rail- way stations, Starbucks and other public locations; tourists can use Global Positioning System (GPS) terminals installed inside rental cars to lo- cate driving maps and tourist attractions, re- searchers 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 ser- vices, 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 mo- bile and Internet terminals will grow yet by an- other 20–50% [280]. With this trend, we can expect the total number of mobile Internet users soon to exceed that of the fixedline 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 net- work 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 ex- tending 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 net work 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 con- clude this section by presenting the design chal- lenges 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, for- warding 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.

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 sup- port 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 infra- structures 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’’ interac- tions, 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 diff erent types of wireless networks with wire-line backbone net- work seamlessly, and convergence of voice, multi- media and data traffc over a single IP-based core network are the main foci of 4G. With the avail- ability of ultra-high bandwidth of up to 100 Mbps, multimedia services can be supported effciently; ubiquitous computing is enabled with enhanced system mobility and portability support, and location-based services are all expected. Fig. 1 illus- trates 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 rep- resents the integration of different types of net- works 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 MEGA- COP, 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 re- duce costs for maintaining separate networks, for different traffic types.

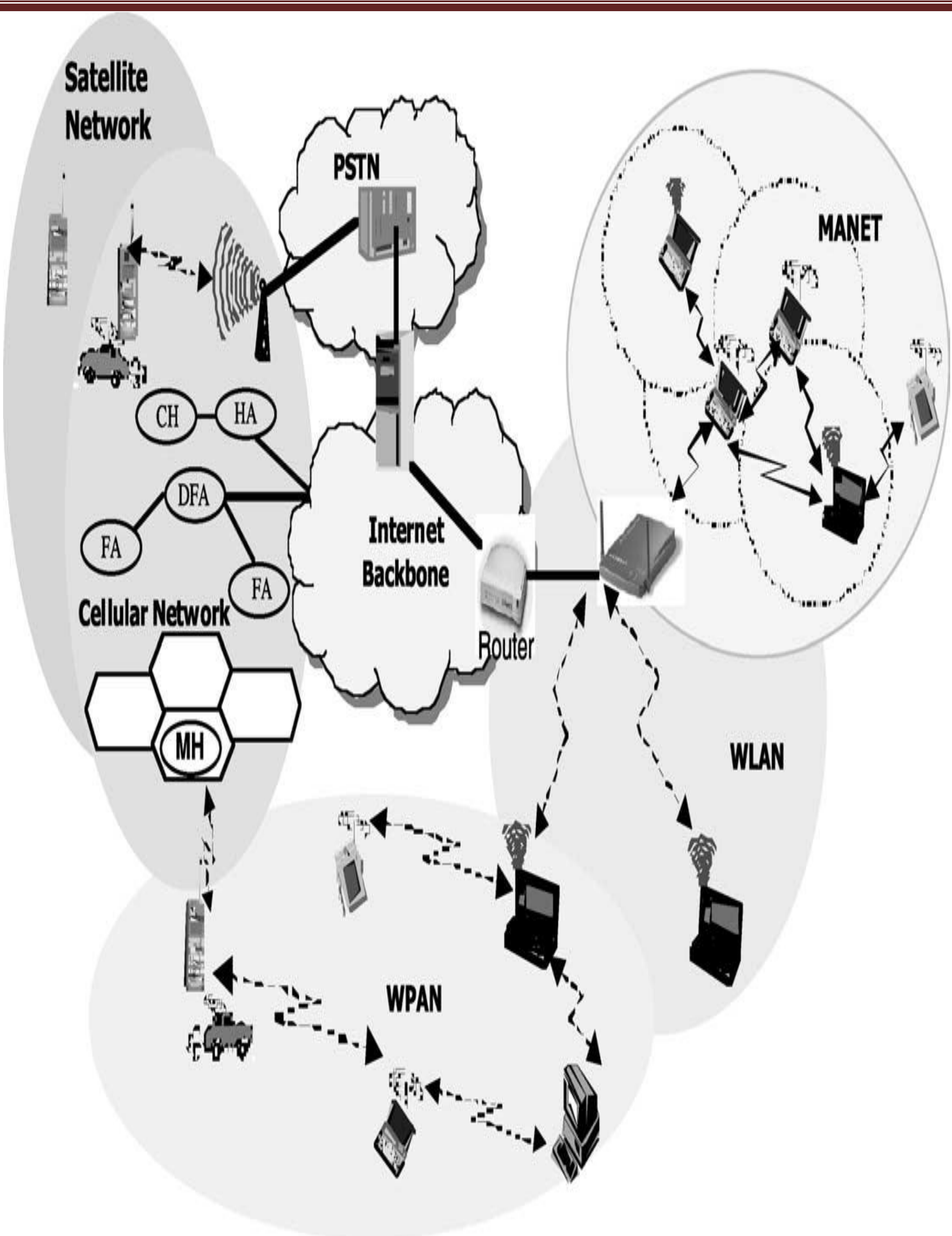

Fig. 1. 4G networks.

Lower Cost and Higher Effciency. 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 infra- structure, 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 de- vices. 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 infra- structure, 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 pre-installed infrastructure. All these advantages make ad hoc networking an attractive option in future wireless networks.

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.

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 hier- archical 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 exam- ple 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 con- necting 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 net- working 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 star- ted to appear (see, e.g., MeshNetworks 1 and SPANworks 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 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 net- work 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 multi- hop nature, and the lack of fixed infrastructure add a number of characteristics, complexities, and design constraints that are specific to ad hoc net- working [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 dy- namic 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 sup- ported 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 for- ward packets from other nodes.

Network scalability. Currently, popular net- work management algorithms were mostly de- signed to work on fixed or relatively small wireless networks. Many mobile ad hoc network applications involve large networks with tens of thou- sands 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.

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 net- works in a systematic/organic way, we will use, as a reference, the simplified architecture shown in Fig. 2.

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 is- sues (energy management, security and cooperation, quality of service, network simulation) span all areas, and we discuss them separately.

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 pre- sent many challenges that are still to be solved (e.g., addressing, routing, location management, security, etc.), and their availability is not on im- mediate horizon. On the other hand, mobile ad hoc networks with smaller coverage can be ex- pected 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 Networks 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, wire- less 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 de- vices. 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 con- nected to the development of networking products at a competitive price. A major factor in achieving this goal is the availability of appropriate net- working 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 Euro- pean 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 net- working 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.

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