Mobile Ad Hoc Networking: Milestones, Challenges, and New Research Directions

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ABSTRACT

In this article we discuss the state of the art of (mobile) multihop ad hoc networking. This paradigm has often been identified with the solutions developed inside the IETF MANET working group, and for this reason it is called the MANET paradigm. However, they do not coincide, and in the last decade they clearly diverged. In this article, we start from the reasons why the MANET paradigm did not have a major impact on computer communications, and we discuss the evolution of the multihop ad hoc networking paradigm by building on the lessons learned from the MANET research. Specifically, we analyze four successful networking paradigms, mesh, sensor, opportunistic, and vehicular networks, that emerged from the MANET world as a more pragmatic application of the multihop ad hoc networking paradigm. We also present the new research directions in the multihop ad hoc networking field: people-centric networking, triggered by the increasing penetration of the smartphones in everyday life, which is generating a people-centric revolution in computing and communications.

INTRODUCTION

The multihop (mobile) ad hoc networking paradigm emerged, in the civilian field, in the 1990s with the availability of off-the-shelf wireless technologies able to provide direct network connections among users devices: Bluetooth (IEEE 802.15.1) for personal area networks, and the 802.11 standards family for high-speed wireless LAN (see Chapters 2 and 3 in [1, 2]). Specifically, these wireless standards allow direct communications among network devices within the transmission range of their wireless interfaces, thus making the single-hop ad hoc network a reality, that is, infrastructureless WLAN/WPAN where devices communicate without the need for any network infrastructure (Fig. 1).

The multihop paradigm was then conceived to extend the possibility to communicate with any couple of network nodes, without the need to develop any ubiquitous network infrastructure. In the '90s, we assisted in the usage of the multihop paradigm in mobile ad hoc networks (MANETs), where nearby users directly communicate (by exploiting the wireless-network interfaces of their devices in ad hoc mode) not only to exchange their own data but also to relay the traffic of other network nodes that cannot directly communicate, thus operating as routers do in the legacy Internet. For this reason, in a MANET, the users' devices cooperatively provide the Internet services, usually provided by the network infrastructure (e.g., routers, switches, servers).

At its birth, the MANET was seen as one of the most innovative and challenging wireless networking paradigms [3], and was promising to become one of the major technologies, increasingly present in the everyday life of everybody. The potentialities of this networking paradigm made ad hoc networking an attractive option for building fourth-generation (4G) wireless networks, and hence MANET immediately gained momentum, and this produced tremendous research efforts in the mobile network community [1, 2, 4].

The Internet model was central to the MANET Internet Engineering Task Force (IETF) working group, which, inheriting the TCP/IP protocols stack layering, assumed an IP-centric view of a MANET; see "Mobile Ad Hoc Networks (MANETs)" by J. P. Macker and M. S. Scott Corson in [1]. The MANET research community focused on what we call *pure general-purpose* MANETs, where *pure* indicates that no infrastructure is assumed to implement the network functions, and no authority is in charge of managing and controlling the network. *General-purpose* denotes that these networks are not designed with any specific application in mind, but rather to support any legacy TCP/IP application, as shown in Fig. 2.

Following this view, the research focused on enhancing and extending the IP-layer routing and forwarding functionalities in order to support the legacy Internet services in a network without any infrastructure. At the network layer, we observed a proliferation of routing protocol proposals as legacy Internet routing protocols developed for wired networks are clearly not suitable for the unpredictable and dynamic

[1] *http://datatracker.ietf.org/wg/manet/charter/*

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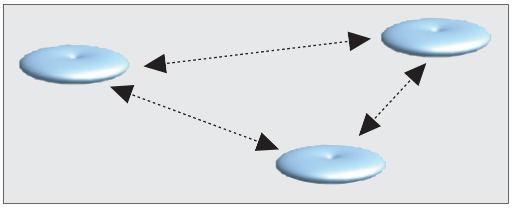

Figure 1. *Single-hop ad hoc network.*

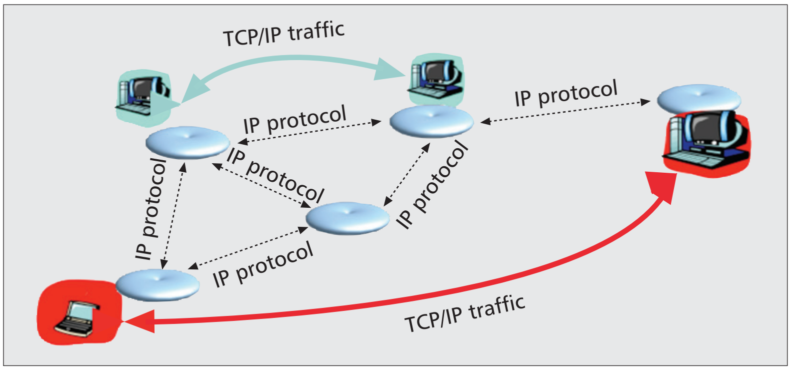

Figure 2. *The pure general-purpose MANET approach.*

nature of MANET topology [4]. Extensive efforts have been dedicated to building a set of standard protocols. However, the released standards protocols, Ad Hoc On-Demand Distance Vector (AODV), Optimized Link State Routing (OLSR), Dynamic Source Routing (DSR), and Topology Broadcast Based on Reverse Path Forwarding (TBRPF) (see the IETF MANET web page[1]) have their pros and cons, and none of them is superior to the others in all contexts. Therefore, they are still under discussion as experimental RFCs. Currently, the group is pursuing a reactive (DYMO, i.e., AODV version 2) and a proactive protocol (OLSRv2).

The research interest rapidly spread from routing to all layers of the Internet protocol stack; [1, 2] present a complete view of MANET research from the physical up to the application layer. On top of the IP, MANET generally assumes the use of the UDP and TCP transport protocols. Unfortunately, TCP does not work properly in this scenario, as extensively discussed in the literature [2]. To improve the performance of TCP in a MANET, several proposals have been presented. Most of these proposals are modified versions of the legacy TCP used in the Internet. However, TCP-based solutions might not be the best approach when operating in MANET environments; hence, several authors have proposed novel transport protocols tailored to the MANET features. On top of that, middleware and applications constitute the less investigated areas in the MANET field. Indeed, in the design of general-purpose MANETs there was not a clear understanding of the applications for which multihop ad hoc networks are an opportunity. Lack of attention to the applications probably constitutes one of the major causes for the negligible MANET impact in the wireless networking field. Lack of attention to the applications also limited the interest to develop middleware solutions tailored on MANETs [2].

In addition to an in-depth re-analysis of all layers of the protocol stack, MANET research also focused on cross-layer research topics with special attention to energy efficiency, security, and cooperation [1].

After more than one decade of intense research efforts, the MANET research field produced profound theoretical results (e.g., performance bounds on MANET performance [5, 6]), or innovative protocol and architectural solutions (e.g., innovative cross-layer architectures and protocols as discussed in [7, Chapter 1]), but in terms of real world implementations and industrial deployments, the pure general-purpose MANET paradigm suffers from scarce exploitation and low interest in the industry and among users [8]. Why has this happened? An initial answer to this question was provided in 2007, in two companion articles that made a critical analysis of the MANET research activities [8, 9] pointing out that the main reasons for MANET's missed expectations are due to the lack of:

- *Implementation, integration, and experimentation*
- *Simulation credibility*
- *Socio-economic motivations*

In addition, that analysis also highlighted that the mesh network, vehicular network, opportunistic network, and sensor network paradigms were originating from the MANET research field. These multihop ad hoc networking paradigms, by learning from the MANET experience, emerged with the promise to avoid MANET's mistakes. Indeed, these new "MANET-born" paradigms distanced themselves from the main weaknesses of the MANET by following a more pragmatic development approach. Currently, six years after that analysis, mesh, sensor, opportunistic, and vehicular networks are a reality in the mobile ad hoc networking field, and their success can be summarized by the following *pragmatic development strategy*:

1 *Application oriented development*, which (as opposed to the general-purpose design of MANET) first identifies the application scenarios to be addressed before starting the development of the technical solutions.
2 *Complexity reduction*. Depending on the specific application scenario, some MANET constraints have been relaxed; for example, the assumption that the network is composed only of users' devices, and/or that the communication model has to comply with the Internet one.
3 The *focused research* approach addresses only the research topics relevant to building robust and effective networks for supporting the specific application scenario(s), and not pretending to replace the Internet.
4 The use of *realistic simulation models* in order to base the protocol development on credible simulation studies.
5 The *development of real network testbeds with the users' involvement*, in the early stages of the design of these new paradigms, in order to put the users in the loop of the network design and experimentation.

In this article, we review the current status of the (mobile) multihop ad hoc networking research. Specifically, we discuss the milestones and challenges in mesh, sensor, opportunistic, and vehicular networks. We also discuss what is foreseen in the future of multihop ad hoc networking. In particular, we discuss the people-centric revolution. Thanks to the increasing diffusion of smartphones, the people-centric paradigm combines wireless communications and sensor networks with the daily life and behaviors of people to build computing and communication solutions that are tightly coupled with people.

We present and discuss mesh, sensor, opportunistic, and vehicular networks, respectively. For each paradigm, we show how the pure and general-purpose MANET paradigm (and the related research results) has been turned into a networking paradigm that has gained users' and market acceptance by exploiting the lessons learned from MANETs. For this reason, the presentation of each paradigm is organized to highlight the main elements of the *pragmatic development strategy*: application-oriented development, problem complexity reduction, focused research, use of realistic simulation models, and development of real network testbeds with the users' involvement. Finally, we conclude by summarizing the paradigms, followed by the introduction of the multi-paradigm vision.

Mesh Networking: An Effective Low-Cost Extension of the Internet

Application-Oriented Paradigm

The design of the wireless mesh network (WMN) paradigm started from a well defined set of application scenarios that is summarized in [10]: "providing a flexible and low cost extension of the Internet." The initial WMN prototypes were mainly driven by the initiatives of communities of users with individual volunteers setting up IEEE 802-11-based long-distance point-to-point links among their houses (Fig. 3) to build a community network and offer a variety of services to their participants, ranging from file sharing and community-wide voice over IP (VoIP) to Internet access through community owned WMN-to-Internet gateways. Nowadays, metropolitan-scale WMNs are a reality in many modern urban areas supported by municipalities and government organizations[2] offering a wide range of services ranging from security surveillance to intelligent transportation services.

Complexity Reduction

Starting from the well defined application scenario, it was immediately possible to reduce the MANET's complexities. Specifically, the WMN paradigm introduces an architectural shift, with respect to MANETs, by adopting a two-tier network architecture based on multihop communications. A multihop wireless backbone is formed by dedicated (and often fixed) wireless mesh routers, which run a multihop routing strategy to interconnect with each other, as illustrated in Fig. 4. Some of the mesh routers act as gateways, providing the WMN with a direct connection to the Internet and other wired/wireless networks. Finally, to support seamless data transport services for users' devices (also called mesh clients), mesh access points are connected to the mesh routers to offer connectivity to mesh clients.

Figure 3. *Community mesh networks.*

Consequently, topology changes due to mobility or energy issues do not influence traffic forwarding in WMNs as in MANETs, and the impact of the mobility is restricted to the last hop (i.e., the connection between the users and the mesh access points).

Focused Research

Following the above architectural organization, the main challenges in WMNs have been subdivided into three main areas:
- Exploiting the wireless mesh routers to build a robust network backbone interconnecting all mesh routers, and possibly some gateways to/from the Internet
- Defining a set of routing protocols that, by exploiting the network backbone, can identify the best path(s) for traffic forwarding inside the WMN and to/from the Internet
- Supporting the users' mobility among mesh access points

All areas have been the subjects of intense research activities providing effective solutions to these problems. In particular, a large body of research focused on building a robust wireless mesh backbone by exploiting advanced multi-radio, multi-channel, and multi-rate capabilities, using heterogeneous wireless technologies and types of antennas [11]. This means that a WMN environment is characterized by a rich link and path diversity, which provides an unprecedented opportunity to find paths that can satisfy the application requirements. Effective channel assignment solutions have been developed to construct robust and efficient wireless mesh backbones ([12, 13]). However, the multifaceted characteristics of a WMN complicate the path selection process. For example, the interference in WMNs is a very complex phenomenon, and the routing process

[2] *See http://www.muni-wireless.com*

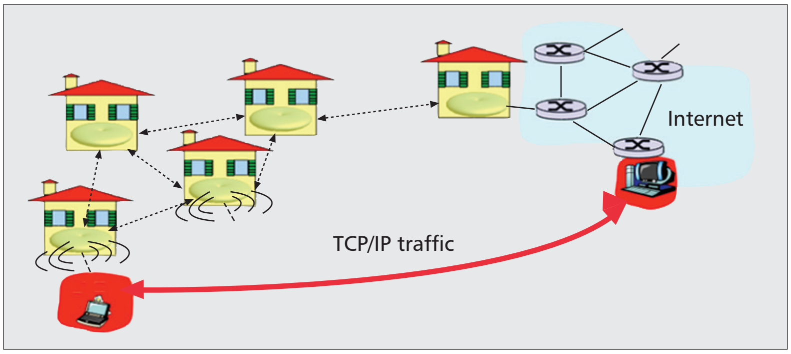

Figure 4. *MESH network two-tier architecture.*

must be aware of the interference existing between links and traffic flows to take advantage of the multi-channel and multi-radio capabilities [14]. In addition, in most application scenarios the portion of traffic a mesh router delivers to other routers in the network (i.e., intra-mesh traffic) will be minimal with respect to the traffic conveyed over connections established with external hosts (i.e., inter-mesh traffic). As a result, most WMN traffic is usually between mesh clients and mesh gateway(s). This implies that traffic gets aggregated at the mesh gateways, which can have a negative effect on network performance. For instance, depending on the network topology and the routing strategy, many mesh routers may select the same gateway, and congestion levels can build up excessively on the shared wireless channel around the gateway. This may also lead to uneven utilization of the gateways' resources. As a consequence, routing protocols must carefully take into consideration the distribution of traffic loads [7, "Quality of Service in Mesh Networks"].

Realistic Simulation and Experimentations with Users

The development of the WMN paradigm has exploited a combined and synergic use of simulation and experimentation [15]. The first phase of this paradigm was dominated by the experimentation of community networks mainly based on the direct use of MANET protocols. The initial success of the WMN paradigm among users stimulated in-depth research activities to develop protocols tuned to the specific features of the WMN. In this second phase, simulation and experimentation were used in a joint way. Experiments were used to investigate the feasibility of the developed solutions in real settings, while simulation studies were used both in the early stages of the protocol design (to compare and contrast alternate solutions) and to study the scalability of the proposed solutions on large networks, thus overcoming the limitations of the real testbeds in terms of network size and scenario diversity. Real testbeds were also useful to set up realistic simulation models and to validate the simulation results [7, "Experimental Work versus Simulation in the Study of Mobile Ad Hoc Networks"].

Current Research

Following the pragmatic development approach, currently WMN is a well-established networking paradigm for which several companies are offering commercial solutions, and WMNs are used to extend Internet connectivity in several metropolitan areas. From a research standpoint, the fundamental aspects of WMNs have been investigated in depth, providing robust solutions for supporting legacy Internet applications. However, some research aspects of this technology are still under investigation to make it more robust and able to support more advanced services requiring quality of service (QoS) support (e.g., video streaming applications [16]), and operating in an energy-efficient way [17].

Sensor Networks: A Market Solution to a Large Range of Problems

Application-Oriented Paradigm

Wireless sensor networks (WSNs) represent a special class of multihop ad hoc networks that are developed to control and monitor a wide range of events and phenomena. Similar to WMNs, WSNs are successful in both academia and industry. WSNs are deployed for specific application scenarios (e.g., precision agriculture [18] and structural monitoring [19]). Thus, the design of these networks highly depends on the specific application scenario and the requirements of the application in terms of reliability, timeliness, and so on. In a WSN, a number of wireless nodes are deployed within the monitoring area, as illustrated in Fig. 5. These wireless nodes can communicate directly among themselves and typically follow the multihop paradigm (through the other sensor nodes) to transmit the collected information toward a sink node. From the sink node, they eventually reach the Internet.

Complexity Reduction

The application driven view and the need to solve a concrete problem was reflected in a natural shift toward a more pragmatic approach. In fact, WSN research always has in mind the real development. Thus, in several cases, WSNs are developed without mobility or with the support of some higher-capacity nodes. For example, when the sensor node density is low, and hence the sensor network is disconnected, mobile elements (also referred to as data mules or message ferries) are used to collect the sensed data and deliver them to the sink [20].

Focused Research

In the last 10 years, WSNs have triggered intensive scientific activities, which has produced a large body of literature to address the WSN research challenges, mostly centered on four main areas [21]:

- *Application network scenarios*: with the coverage of a wide range of application targets and scenarios [22]

- *Communication protocols for WSN*: medium access control (MAC) protocols, routing protocols, clustering algorithms, security, networks with mobile nodes, and so on [23, 24]
- *Hardware and software sensor system*: characteristics and requirements for a sensor node [25], system platforms and operating system (OS), testbeds, diagnostics, and debugging support
- *Network services and WSN optimization*: from hardware advances to the understanding of physical-related phenomena with the design of algorithms and schemes for energy efficiency, time and clock synchronization, security, coverage and connectivity, security and localization, network performances, and so on [26]

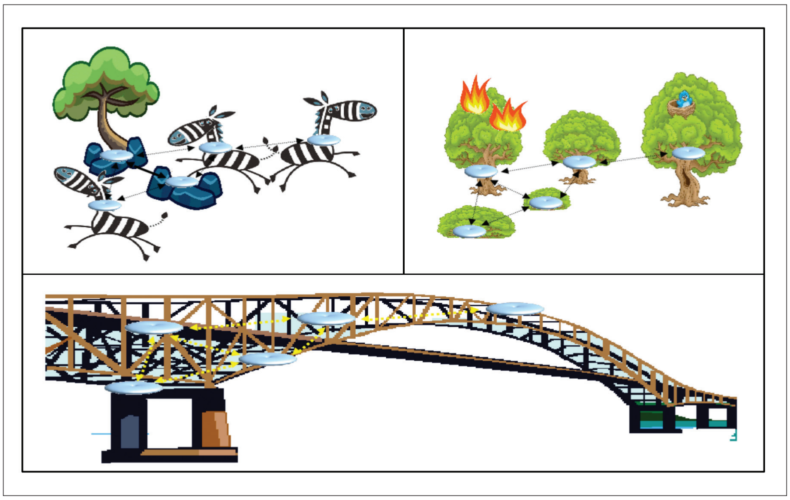

Figure 5. *WSNs are often pure, as are traditional MANETs, but they are application specific, as shown in those figures: wild animal monitoring, construction monitoring, and fire prevention.*

REALISTIC SIMULATION AND EXPERIMENTATION WITH USERS

The need for real development produced an orthogonal approach to MANET validation. While initially simulation was largely used [27], it was quite soon replaced by large testbeds deployed at several universities,[3] which are open for access to the research community. This allows validation with real sensor nodes, and the final results, which are finally given to the end user, are necessarily collected in a real deployment. One of the largest sensor network deployments in the world (with about 5000 sensors connected to same base station) is the GreenOrb[4] WSN, which uses several types of sensors (for measuring temperature, humidity, illumination, carbon dioxide, etc.) for forest surveillance.

CURRENT RESEARCH

We can argue that legacy WSN is a very well consolidated area, and mainly specialized network scenarios are still researched. However, some additional complementary issues are still matters of research, such as:
- Problems related to privacy, security and trust [28, 29]
- Network performance [30]
- User-friendly development [31]

Furthermore, new WSN paradigms are emerging, such as:
- Energy harvesting WSNs
- WSNs with robots
- Underwater WSNs
- The use of mobile phones as a human-centric sensing tool

Hereafter, we discuss the first three, while the fourth is discussed later.

Energy harvesting WSN: In [7, "Wireless Sensor Networks with Energy Harvesting"], the authors explore the opportunities and challenges of energy-harvesting-based WSNs (EHWSNs), which result from endowing WSN nodes with the capability of extracting energy from the surrounding environment. Energy harvesting can exploit different sources of energy, such as solar power, wind, mechanical vibrations, temperature variations, magnetic fields, and so on. By continuously providing energy and storing it for future use, energy harvesting subsystems enable WSN nodes to last potentially forever. This benefit opened new directions of investigation like efficient energy storing, optimal techniques for energy harvesting, and energy prediction models for predictable power sources (mainly solar and wind). On top of EHWSNs, task allocation protocols constitute a highly studied area given that the design objectives of communication protocols have moved from energy conservation to opportunistic optimization of the use of the harvested energy.

WSNs with robots: Despite the plethora of successful application in several domains, WSNs are still prone to operational events that arise during deployment, maintenance, or replacement. Wireless sensor and robotic networks (WSRNs) entrust those tasks to resource-rich mobile robots tending resource-constrained stationary sensors [32]. Actions are collaboratively executed by the robotic agents on the basis of the information received by deployed standalone sensing units, as surveyed in [7, "Robot-Assisted Wireless Sensor Networks: Recent Applications and Future Challenges"]. Thanks to the latest advances in multi-robot systems, the WSN's operational tasks can be simplified and are now studied from the robot intervention standpoint, and distribution of task and multi-robot coordination are now the major challenges.

Underwater WSN: Reference [7, "Underwater Networks with Limited Mobility: Algorithms, Systems, and Experiments"] discusses how WSNs can be employed in the underwater environment, where lack of feasible recharging solutions limits power, and nodes leverage their limited mobility for increased functionality and extended lifetime. In this case, WSNs combine a fixed location with some mobility similar to that of water column profilers. However, to improve sensing quality while optimizing system lifetime, the system needs automated intelligence to allow each node to optimally place itself, such that the overall system best captures the variable of interest (which usually changes over both time and space). Any solution must be robust to communication failures in the network, as well as power efficient. Reference [7, "Advances in Underwater Acoustic Networking"] complements the previous work with a comprehensive account of

[3] *See, for example, Motelab http://motelab.eecs.harvard.edu/ , Twist http://www.tkn.tu-berlin.de/menue/telecommunication_networks_group/ and Indriya http://indriya.comp.nus.edu.sg/*

[4] *http://www.greenorbs.org/*

While a MANET represents an engineering approach to hiding node mobility by constructing "stable" end-to-end paths as in the Internet, opportunistic networks do not consider node mobility as a problem but as an opportunity to exploit.

recent advances in underwater acoustic communications and networking. Transmission techniques, architectures, protocols, and algorithms for underwater networking are being actively researched. In underwater WSNs, acoustic communications are a more valid solution than traditional radio frequency (RF) communications, due to the latter's transmission requirements in such environment. Still, due to the physical properties of the propagation medium, underwater acoustic signals suffer from severe transmission loss, time-varying multipath propagation, Doppler spread, limited and distance-dependent bandwidth, and high propagation delay, generating links unreliability and severe limits in the available bandwidth.

Opportunistic Networking: A First Step in People-Centric Networking

Application Oriented Paradigm

Opportunistic networking is one of the most interesting evolutions of the multihop networking paradigm. Indeed, while MANET represents an engineering approach to hide node mobility by constructing "stable" end-to-end paths as in the Internet, opportunistic networks do not consider node mobility a problem but as an opportunity to exploit. In opportunistic networks the mobility of nodes creates contact opportunities among nodes, which can be used to connect parts of the network that are otherwise disconnected. Specifically, according to this paradigm (also referred to as delay-tolerant or challenged networks), nodes can physically carry buffered data while they move around the network area until they get in contact with a suitable next-hop node (i.e., until a forwarding opportunity exists). Thus, as opposed to a MANET, a node keeps on storing data when no good next hop exists. This implies that, with the opportunistic paradigm, a data can be delivered from a source toward a destination, even if an end-to-end path between them never exits, by exploiting the sequence of connectivity graphs generated by nodes' movement [33, 34]. This is a relatively young paradigm, and opportunistic network research is still ongoing. Therefore, one may argue that its impact is still to be proved. However, given that we can consider vehicular ad hoc networking (VANET) one of the most advanced and concrete developments of the opportunistic networking paradigm, we can claim that the opportunistic network paradigm already has a significant role in the computer networking field.

In addition to VANET, other scenarios, motivating opportunistic network use, are discussed in [7, "Applications in Delay-Tolerant and Opportunistic Networks"]. Opportunistic networking looks very suitable for communications in pervasive environments where the environment is saturated by devices (with short-range wireless technologies) that can self-organize in a network for local interactions among users. In these scenarios, the network is generally partitioned in disconnected islands, which might be interconnected by exploiting the nodes' mobility. This implies a shift from legacy packet-based communication, toward message-based communication, bringing along new opportunities for application protocol design.

Complexity Reduction

Opportunistic networking departs from the Internet-oriented approach used in MANETs as it does not impose an end-to-end path from source to destination. This eliminates the huge effort of hiding node mobility, which caused high complexity in MANETs. In opportunistic networking the multihop networking paradigm becomes best effort (without the need to maintain paths or tables) and user-centric, and (human) mobility becomes an opportunity for communicating.

Focused Research

Three main directions have characterized the opportunistic networking research: mobility models, routing protocols, and data dissemination.

Mobility models: Understanding and modeling the properties of the human mobility is crucial for characterizing the constraints of opportunistic communications, and designing practical and effective forwarding strategies [35, 36]. Major elements of human mobility characterization are the *contact time*, the distribution of the contact duration between two devices, and the *inter-contact time* (ICT), the distribution of the time between two consecutive contacts between devices. In particular, the characterization of the ICT distribution has generated a great debate in the scientific community where different research groups have claimed completely different results ranging from heavy-tailed distribution functions — with [37] or without [38] an exponential cutoff — to an exponential distribution [39]. In [40], the authors have shown a fundamental result that helps explain the differences among the different ICT distributions observed in the literature. Understanding the properties of ICT distribution is a critical issue due to the fact that on this distribution depends the effectiveness of several routing protocols for opportunistic networks. For example, in [38] the authors have shown that for a simple forwarding scheme, like the two-hop scheme, the expected delay for message forwarding might be infinite depending on the properties of the ICT distribution. Reference [7, "Mobility Models in Opportunistic Networks"] introduces recent measurement studies on human mobility and realistic mobility models.

Routing: Opportunistic routing protocols have to face three main problems:

- The uncertainty of future connectivity
- The characteristics of human (or vehicular) mobility
- The heterogeneity of node resources and mobility

Replication techniques are used to cope with the first obstacle, while utility-based forwarding techniques are used for the second and third ones. As indicated in [7, "Opportunistic Routing"], opportunistic routing schemes are mainly built on one or more of the following basic mechanisms:

- Mobility-assisted mechanism: Store-and-carry a message until there is a communication opportunity;

- Local forwarding mechanism: Decisions are made to bring the message probabilistically closer to its destination.
- Replication mechanism: Propagate multiple copies of the same message in parallel, to increase the probability of at least one being delivered.
- Coding mechanism: Source coding and network coding techniques are used to reduce performance variability and improve resource usage.

However, due to the large variety of scenarios and characteristics, no single routing scheme is optimal for every application scenario.

Data dissemination: This represents a concrete application scenario in opportunistic networking in which nodes usually play both roles of "publisher" and "subscriber" at the same time. Several dissemination strategies — classified in six main categories in [7, "Data Dissemination in Opportunistic Networks"] — have been proposed, based on the specific problem targeted and the type of solution proposed:

- Popularity-based strategies: drive the selection of content items to be cached based on the popularity of the content itself
- Social-behavior-based strategies: selection performed based on users' social dimension
- Publish/subscribe strategies: selection based on content-centric overlays
- Global-optimality-based strategies: a global optimization solution approximated by a local one
- Heterogeneous-technologies-based strategies: selection realized by combining the broadband wireless infrastructure with an opportunistic network of user devices
- Peer-to-peer (p2p) strategies: selection performed using approaches similar to unstructured p2p systems.

Realistic Simulation and Experimentations with Users

Learning from MANET experience, opportunistic-network researchers have spent lot of efforts to develop realistic simulators (e.g., ONE[5]) and experimental testbeds [41]. As humans typically carry the devices, it is the human mobility that generates the communication opportunities, as illustrated in Fig. 6. Thus, opportunistic-network experiments, necessarily, involves real users. Studying human mobility traces is the starting point to understand the properties of the human mobility, with the aim of providing a characterization of the temporal properties of devices/humans mobility. Therefore, these experiments are also used to derive mobility models, which are the basis for realistic opportunistic-network simulations.

Current Research

In addition to the activity in three main areas discussed above, the research community is currently investigating the interchange between opportunistic networking and the social characteristics of people. Indeed, mobile devices act as proxies of the humans in the cyber world and thus inherit the social links of their owners [42]. In this sense, an emerging research area in opportunistic networking is related to the characterization of the social behaviors. In [43] there is a first attempt to link the similarity of social characteristics (homophily) of humans with the probability of contacts, thus connecting the opportunistic networking with a large research area in human sciences. Another new relevant area that is emerging from opportunistic networking is opportunistic computing [41]: the services present on users devices can get opportunistically distributed and combined accordingly to users interests and needs. Projects as EU FP7-FIRE SCAMPI ("Service platform for social Aware Mobile and Pervasive computIng"), US NSF DoC ("Distributed Opportunistic Computing"), and EIT-ICT Lab MONC (Mobile Opportunistic Networking and Computing) are opening the research path in opportunistic computing.

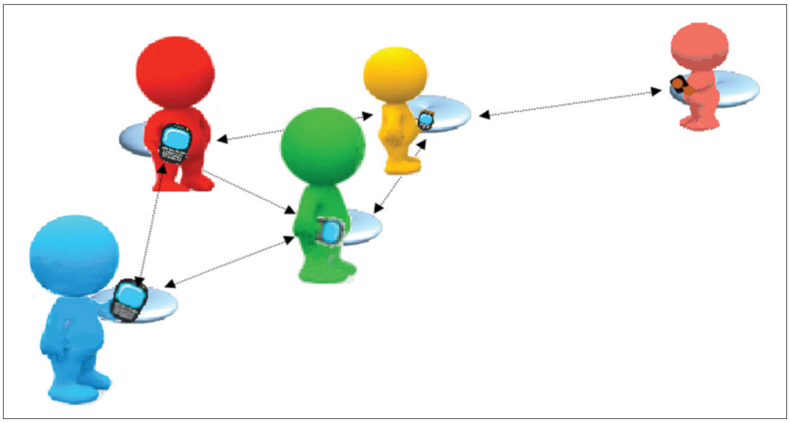

Figure 6. *Opportunistic networking is based on human mobility.*

Vehicular Networking

Application Oriented Paradigm

A vehicular ad hoc network (VANET) is a multihop ad hoc network made up of vehicles that communicate among them by exploiting wireless technologies (typically) belonging to the 802.11 family. This is a specialization of multi-hop ad hoc network paradigm well motivated by the socio-economic value of advanced Intelligent Transportation Systems (ITS) aimed at reducing the traffic congestions, the high number of traffic road accidents, etc. Indeed VANET can support a large plethora of applications including safety traffic applications (e.g., collision avoidance, road obstacle warning, safety message disseminations, etc.), traffic information and infotainment services (e.g., games, multimedia streaming, etc.). For example, a car involved in an accident can exploit the possibility to directly communicate with other vehicles to inform nearby vehicles of the dangerous situation. An extensive survey of the vehicular applications is presented in [44].

Complexity Reduction

Advanced ITS systems require both vehicle-to-roadside (V2R) and vehicle-to-vehicle (V2V) communications. In V2R communications a vehicle typically exploits infrastructure-based wireless technologies, such as cellular networks, WiMAX and WiFi, to communicate with a roadside base

[5] *http://www.netlab.tkk.fi/tutkimus/dtn/theone/*

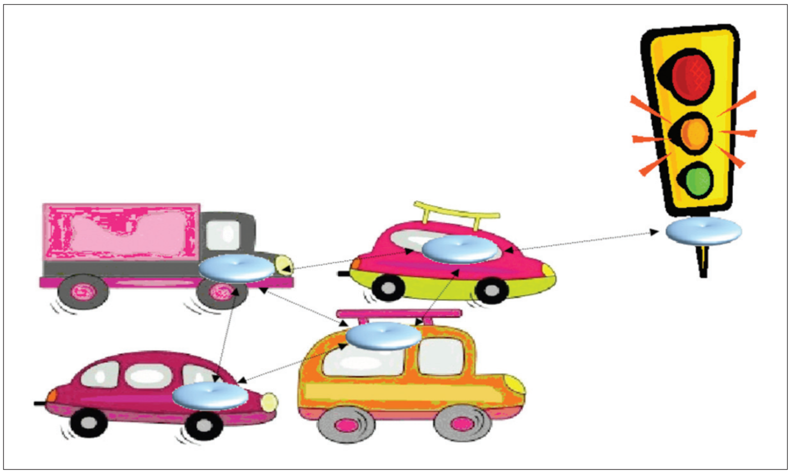

Figure 7. *VANET.*

station/access point. However the roadside units are not dense enough to guarantee the network coverage required by ITS applications and hence V2V communications are adopted to extend the network connectivity/coverage and to guarantee better network performance.

V2V communications are based on the "pure" multi-hop ad hoc network paradigm as MANET. Specifically, according to this paradigm, the vehicles on the road dynamically self-organize in a VANET by exploiting their wireless communication interfaces, see Fig. 7. However the high level of vehicles' mobility and the possibility of sparse networking scenarios, which occur when the traffic intensity is low, make inefficient the legacy store-and-forward communication paradigm used in MANET and push toward the adoption of the more flexible, pragmatic and robust store-carry-and-forward paradigm adopted by the opportunistic networks (see the "Opportunistic Networking" section). In addition, whenever possible, V2V communications exploit V2R communications to make their communications more robust reducing some weaknesses and vulnerabilities of pure infrastructure-less communications.

The high socio-economic value of vehicular applications pushed the international standardization bodies to develop technical specifications to be adopted by vehicle industry. Among these it is worth reminding the IEEE 1609 standard family for Wireless Access in Vehicular Environment (WAVE) that has been developed upon the IEEE 802.11p standard. Typically, power consumption is not an issue for this network as vehicle batteries are continuously recharged.

FOCUSED RESEARCH

V2R communications exploit well-established technologies (WiFi, WiMAX, Zigbee, etc.) operating in infrastructure-based mode (e.g., see "Enabling Technologies and Standards for Mobile Multihop Wireless Networking" [7]). Their adoption in vehicular networks requires a careful analysis of their performance when operating in highly dynamic environments where the connection time between the vehicle and the roadside unit may be short and/or several vehicles are connected to the same roadside unit (scalability issue).

The V2V research field inherited MANET results related to multi-hop ad hoc routing/forwarding protocols [45], which have been tuned and modified for adapting them to the peculiar features of the vehicular field [46]. The routing task is challenging in VANET due to the high mobility of vehicles which are intermittently connected. However, in VANET, the mobility of the network nodes (i.e., vehicles) is constrained by the road characteristics and the other vehicles moving along the road. Special attention has been reserved to the development of optimized one-to-all (in a specific region) routing protocols as several applications developed for VANET use broadcasting (geocasting) communication services [47] to distribute a message from a vehicle to all other vehicles (in a given area). Broadcasting or geocasting are also the basic communication services for content dissemination in a VANET, i.e., the dissemination to other vehicles of a file containing relevant information (e.g., a city map or infotainment information such as a music mp3 file). Due to the intermittent connectivity conditions, the opportunistic paradigm applied to vehicular networks has recently generated a large body of literature mainly on routing protocols and data dissemination in vehicular networks (e.g., [48, 49]).

REALISTIC SIMULATION AND EXPERIMENTATIONS WITH USERS

Both simulation and experimentation have a major role in designing and evaluating the solutions developed for vehicular networks. In the simulation of vehicular networks a lot of attention has been dedicated to develop realistic models of roads and of the vehicle mobility by exploiting the extensive literature developed in the field of transportation systems, e.g., models of how cars move along a road taking into consideration their speeds, the distance among them, traffic signals, the road layout, etc [50].

Several well-known network simulator like ns-2, ns-3, SWANS, OMNET++, OPNET, etc., are able to take as input trace files, generated by specialized vehicle mobility models (e.g., VanetMobiSim and SUMO), which provide realistic vehicle mobility behaviours. However, in some scenarios, the interdependences among vehicle communications and their mobility patterns make the problem more complex. For example, when a congestion/accident occurs the communication among vehicles influences their mobility by triggering a road change and/or a speed reduction. For this kind of simulation the above approach is not suitable and therefore the VANET community is currently developing simulators which are able to take into account the interdependencies between the vehicles' mobility and their communications. For example, TraNS (Traffic and Network Simulation environment) integrates ns-2 and SUMO by providing feedbacks from the network simulator (ns-2) to affect the mobility traces produced by the SUMO mobility simulator.

Another important aspect to consider (to produce realistic VANET simulations) is related to the simulation of the wireless channel among vehicles and to/from roadside units taking into account how the radio signal propagates in this environment.

An updated and in-depth discussion of VANET simulation models and tools can be found in "Mobility Models, Topology and Simulations in Vanet" [7].VANET prototypes have been extensively used to verify the feasibility of VANET solutions and the effectiveness of VANET applications. For these reasons several testbeds have been developed worldwide. Among these, it is worth remembering the CarTel project at MIT (which developed a 27-car testbed for testing V2V, V2R, road surface monitoring, etc.), the DiselNet project at UMass (which is based on 35 buses which implement a DTN-based communication paradigm), the ShanghaiGrid project (which involves thousands of taxies and buses for vehicle and traffic monitoring and environment sensing) and the pioneering FleetNet project (involving several companies and universities in Germany to demonstrate their platform for inter-vehicle communications). An updated survey of VANET experimental activities can be found in "Experimental work on Vanet" [7].

Current Research

Several interesting and challenging issues are still to be addressed in the VANET field; a special attention should be reserved to develop realistic models to characterize the mobility of the VANET nodes [50], and to analytically study the performance of 802.11 technology in VANET [51]. Current research is also intensive on data communication. A survey is presented in the chapter by Awwad, Yi, and Stojmenovic in [7]. A fsew other chapters in the same book survey the ongoing research activities on experimental testbeds and simulation tools.

The People-Centric Revolution

Application-Oriented Paradigm

In mobile multihop networking, the technology characteristics can be naturally combined with people's behaviors and daily life events, allowing the definition of a first example of a networking paradigm that puts people in the center, as the network is built with the people's devices. This has become more and more true and real with the recent emergence of smartphones. In fact, the major innovation introduced by mobile phones is that they do move, and move with people (the owners). For this reason, the networking paradigms based on those devices (e.g., mobile phone sensing, opportunistic networking/computing, or mobile cloud computing) are shifting from a device-to-device paradigm toward a person-to-person paradigm: the people-centric vision [52]. This vision, as clarified below, considers the knowledge and experience in MANETs. As for opportunistic networking, being centered around people's mobile devices makes this paradigm very application oriented, while opening up new research challenges related to human mobility.

Complexity Reduction

The people-centric paradigm privileges the top-down approach, taking into account people's needs and constraints first. The network, in terms of connections, data, and resources, builds with people, leaving no room for traditional system-oriented approaches. This generates a cyber-physical convergence as the mobile phone acts as a proxy of human behavior in the cyber world. While people really move into the physical dimension, their mobile phones project their movements in the cyber world.

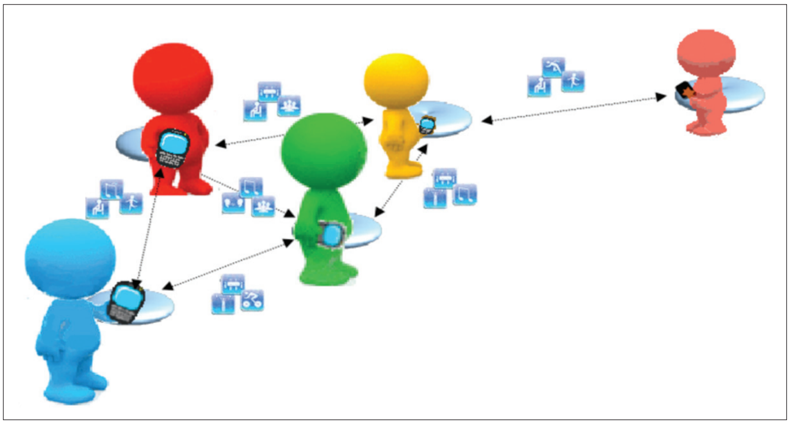

Figure 8. *Mobile phone sensors used for participatory sensing.*

Realistic Simulation and Experimentations with Users

Clearly, evaluation of people-centric solutions must be done by users. Even in the case of simulation, some real human traces are necessary.

Focused Current Research

As discussed below, the main directions of people-centric networking are:
- Mobile phone sensing: where billions of users' mobile devices/phones are used as location-aware data collection instruments for real world observations
- Mobile phone cloud: where people's devices are used to offer a cloud computing service

Mobile Phone Sensing

In mobile phone sensing (also known as *crowd sensing*) the physical world is sensed without deploying a sensor network: it creates a *participatory sensor network* where people take an active role in the decision stages of the sensing system [53]. A participatory system provides tools to share, publish, search, interpret, and verify information collected using a custodian device [54]. In *opportunistic sensing* the sensing activities are performed by the (opportunistic) exploitation of all the sensing devices available in the environment whenever there is a match with the application requirements. In addition, multi-modal sensors spread in the environment can be exploited opportunistically to infer precise information about the social behavior of the users and the social environment around them. Indeed, participatory and opportunistic sensing offers unprecedented opportunities for *pervasive urban sensing* [55]: to effectively *collect* and *process* the digital footprints generated by humans when interacting with the surrounding physical world and the social activities therein. A major goal of these sensing activities is to investigate the hybrid city (i.e., a city that operates simultaneously in the cyber/digi-

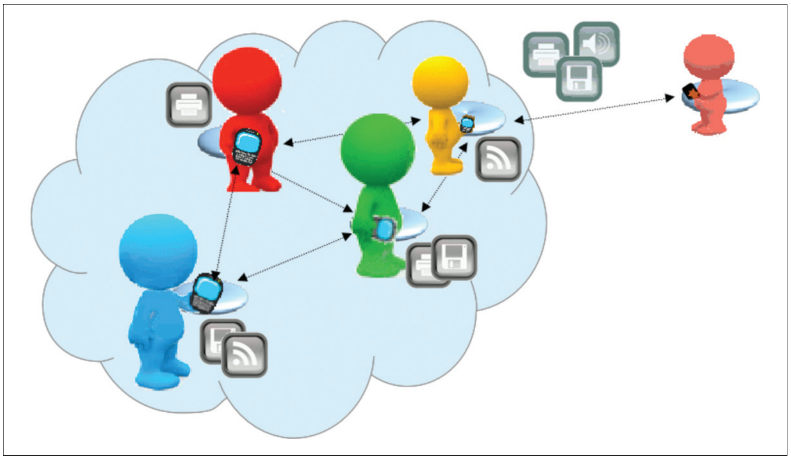

Figure 9. *Mobile phone cloud — users can get computing facilities from other users.*

tal and physical realms) to investigate human behavior and socio-economic relationships ([56, 57]). This is a highly challenging and innovative research objective that can bring the development of novel urban applications that benefit citizens, urban planners, and policy makers. Preserving the privacy of individuals while contributing their sensed data is a major challenge for progressing toward pervasive urban sensing [58].

Mobile Phone Cloud

Cloud computing has gained momentum in the last years as a response to the high increase of service requests derived from *new* high resource-consuming applications: the computing resources (hardware and software) are delivered as a service over the Internet. While this new service model has shown to be very powerful, it is associated with a high energy cost in accessing the services themselves. As shown by several notable studies in the smartphone community [59, 60], accessing remote computing resources requires end devices to invest a significant amount of their energy resources.

Mobile smart devices are becoming more and more capable, and will be increasingly able to offer more and more services, effectively serving as a *mobile cloud*. By pooling their resources and encouraging their opportunistic exploitations by resource-poor devices, mobile smart devices can streamline the sustainable scalability of the Future Internet by bringing services and resources closer to where they are needed, thereby lowering the energy premium paid by resource-constrained systems [52].

The importance of mobile cloud computing grows with the proliferation of mobile phone devices and ubiquitous computing resources. Rather than seeking cloud services from a faraway data center, we envision that tomorrow's embedded systems will seek cloud services from smart mobile devices in their surroundings [52]. This will enable the exploitation of the vast array of resources available on user devices and, at the same time, permit significant energy savings for embedded systems, which will not have to pay the energy premium required to access a distant cloud. However, there is clearly a trade-off: the (exclusive) local execution of computationally intensive tasks is necessarily a suboptimal approach. At the opposite end, cloud computing offers high-end resources at a non-negligible energy cost. If we stop looking at mobile communication technologies simply as a means to connect a mobile device to the infrastructure, and abolish the strict consumer–operator service model, we can begin to see the true potential of today's mobile devices and the additional communication opportunities arising from direct device-to-device contacts [52]. This is clearly centered around users: they play both the roles of consumer and producer, sometimes eager to share their resources with other people. Also, some more popular resources are likely to exist on devices close to the user, thus allowing energy and time savings.

This naturally leads to the opportunistic computing vision, where services can be combined across multiple nodes, are offered by any node, and can be offloaded to any node (and not just a special subset of infrastructure nodes). Thus, opportunistic computing offers a distributed mobile cloud, that is, a computing system that harnesses the CPU, memory, energy, and sensing resources of multiple nodes of heterogeneous capabilities that collectively form a cloud that is distributed in both space and time [52]. Each node in the distributed cloud corresponds to a pairwise encounter, and may therefore provide useful local context information, which is something that a distant computing cloud would not be able to give.

Specifically, as indicated in Fig. 9, individual devices may combine and exploit each other's resources to boost their computing power and overcome the limitations of their own resources [41], without the communication energy footprint and extreme centralization of cloud computing. Therefore, the distributed mobile cloud model offered by opportunistic computing can be seen as the means to provide energy-efficient computing access to resource-constrained devices.

Summary and Conclusions: Toward a Multi-Paradigm Era

While the MANET stimulated some decades of research efforts, it did not significantly impact the wireless networking market, due to several weaknesses in its original design and in the research approach, as extensively discussed in previous works [7, Chapter 1; 8]). However, the lessons learned from MANET experience provide the basis for a pragmatic development strategy that has been applied in the development of several "MANET-born" communication network paradigms— mesh, sensor, opportunistic, vehicular, and people-centric networking – which are, or soon will be, successful and widespread. In this article we have extensively discussed these emerging networking paradigms, showing that their design and deployment can be described according to the five points of the pragmatic development strategy: application oriented development, complexity reduction, focused research, realistic simulation models, and development of real network testbeds.

For each paradigm, we have summarized the main features, research challenges and solutions, and current status of deployment. While mesh, sensor, and vehicular networks already have a

	Market relevance	Application scenarios	Research interest	Open research issues
MANET	Decreasing	Niche (military and safety)	Low and decreasing	Standardization
WMN	High	Smart cities	Medium but decreasing	QoS, performance optimization
WSN	High	Ambient intelligence, pervasiveness, monitoring, and controlling	High	User-friendly development, performance, mobility, WSRN, under-water, and acoustic sensor networks
OppNet	Medium but increasing	Mobile social networking Data dissemination, offloading	Increasing	Privacy, performance, communication approaches, and architectures
VANET	High	Road safety, traffic efficiency, infotainment	High	QoS support, reliable broadcasting protocols, and standardization
People-centric	Medium but increasing	Social-based scenarios, mobile phone scenarios	Increasing	Privacy, performance, service approaches, and architectures

Table 1. *Summary of MANET-born paradigms.*

major role in the pervasive networking market, the opportunistic networking and people-centric paradigms are attracting a growing interest strongly coupled with the increasing use of smartphones, and are expected to become central in the coming years. Table 1 presents a summary of the current status of research and market trends in these paradigms, and compares them with MANET.

It can be expected that in the near future the above paradigms will be mixed together and/or integrated with infrastructure-based networks, thus generating novel networking paradigms, merging the self-* feature properties of multihop ad hoc networks and the reliability and robustness features of infrastructure-based networks. Major examples of this trend are hybrid cellular-opportunistic networks, which aim to mitigate the cellular data traffic problems (by offloading some traffic by opportunistically exploiting the users' devices), and vehicular networks, where opportunistic networking techniques are exploited to overcome the coverage limitations of roadside infrastructure-based networks. More generally, we can envisage complex application scenarios where several networking paradigms are mixed together, like the one illustrated in Fig. 10, where each paradigm does not act in isolation, but there is sharing among them, with mutual benefit: the multi-paradigm era.

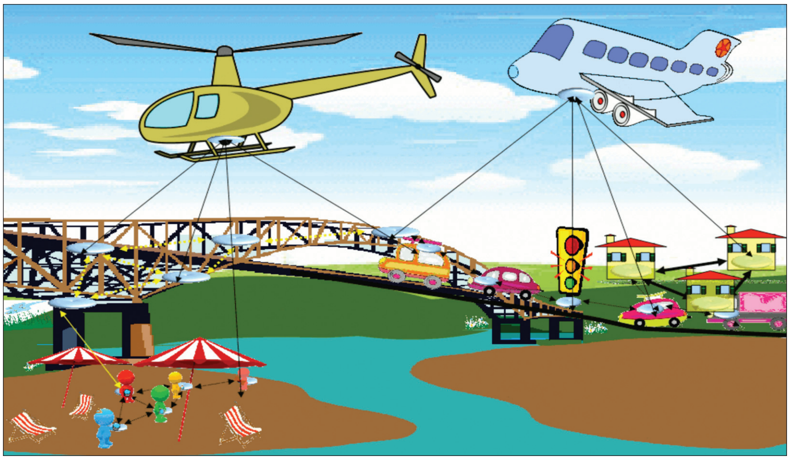

Figure 10. *The multi-paradigm era.*

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We can envisage complex application scenarios, where several networking paradigms are mixed together where each paradigm does not act in isolation, but there is a sharing among them, with mutual benefit: the multi-paradigm era.

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