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From MANET to people-centric networking: Milestones and open research challenges

Marco Conti [a,*], Chiara Boldrini [b], Salil S. Kanhere [c], Enzo Mingozzi [d], Elena Pagani [b,e], Pedro M. Ruiz [f], Mohamed Younis [g]

[a] Consiglio Nazionale delle Ricerche, Department of Engineering, ICT and Technologies for Energy and Transport, Italy
[b] Consiglio Nazionale delle Ricerche, Institute of Informatics and Telematics, Italy
[c] The University of New South Wales, School of Computer Science and Engineering, Australia
[d] Università di Pisa, Department of Information Engineering, Italy
[e] Università degli Studi di Milano, Department of Computer Science, Italy
[f] Universidad de Murcia, Department of Information and Communications Engineering, Spain
[g] University of Maryland, Baltimore County (UMBC), Department of Computer Science and Electrical Engineering, USA

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ABSTRACT

In this paper, we discuss the state of the art of (mobile) multi-hop ad hoc networking with the aim to present the current status of the research activities and identify the consolidated research areas, with limited research opportunities, and the hot and emerging research areas for which further research is required. We start by briefly discussing the MANET paradigm, and why the research on MANET protocols is now a cold research topic. Then we analyze the active research areas. Specifically, after discussing the wireless-network technologies, we analyze four successful ad hoc networking paradigms, mesh networks, opportunistic networks, vehicular networks, and sensor networks that emerged from the MANET world. We also present an emerging research direction in the multi-hop 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.

1. Introduction

This article discusses the state of the art of (mobile) multi-hop ad hoc networking [1]. The aim is (i) to point out research topics that have been extensively researched and are now cold research areas, for which further research is not recommended, and (ii) to identify the hot and emerging research challenges that still require extensive investigations.

The multi-hop (mobile) ad hoc networking paradigm emerged, in the civilian field, around 90′s with the availability of off-the-shelf wireless technologies able to provide direct network connections among users devices: Bluetooth (IEEE 802.15.1), for Wireless Personal Area Network (WPAN), and the IEEE 802.11 standards' family for high-speed Wireless LAN (WLAN), see Chapters 2–4 in [2]. Specifically, these wireless standards allow direct communications among network devices within the transmission range of their wireless interfaces thus making single-hop ad hoc network a reality, i.e., infrastructure-less WLAN/WPAN where devices communicate without the need of any network infrastructure.

The multi-hop paradigm was then conceived to extend the possibility to communicate to any couple of network nodes, without the need to develop any ubiquitous network infrastructure: 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 the routers do in the legacy Internet [3]. This paradigm has been often identified with the solutions developed inside the MANET IETF working group, and for this reason was often called the MANET paradigm [4].

At its birth, MANET was seen as one of the most innovative and challenging wireless networking paradigm and was promising to become one of the major technologies, increasingly present in everyday life of everybody. Therefore, MANET immediately gained momentum and this produced tremendous research efforts in the mobile-network community [5]. MANET research focused on what we call *pure general-purpose* MANET, where *pure* indicates that no infrastructure is assumed to implement the network functions and no authority is in charge of managing and controlling the network. *General-purpose* denotes that these networks are not designed with any

* Corresponding author.
E-mail address: marco.conti@iit.cnr.it (M. Conti).

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specific application in mind, but rather to support any legacy TCP/IP application. Following this view, the researchers 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 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 nature of MANET topology. The research interests rapidly spread from routing to all layers of the Internet protocol stack, from the physical up to the application layer [6], however applications, probably constitutes the less investigated area of MANETs. Indeed, in the design of general-purpose MANETs, there was not a clear understanding of the applications for which multi-hop ad hoc networks are an opportunity. Lack of attention to the applications, probably, represents one of the major causes for the negligible MANET impact in the wireless networking field.

After about two decades of intense research efforts, the MANET research field produced profound theoretical results (e.g., performance bounds on MANET performance [6,7]), or innovative protocols and architectural solutions (e.g., cross-layer architectures and protocols) [5], 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 the users [4]. Therefore, in the last years, the interest for the MANET paradigm has been rapidly decreasing and the research on MANET protocols can now be considered a cold research topic. Indeed, it is interesting to observe that the number of manuscripts focusing on MANET, published in top quality journals, is rapidly decreasing.[1]

Even though MANET research has not a major impact on the wireless networking field (except for specialized fields such as military and disaster recovery), several networking paradigms have emerged from the MANET field that are currently generating interest both in the academia and industry. Among these, let's remember: mesh networks, vehicular networks, opportunistic networks and sensor networks. These multi-hop ad hoc networking paradigms, by learning from the MANET experience, emerged from MANET by avoiding the main weaknesses of the MANET research by following a more *pragmatic development strategy* [4].

In this article, after a review of the current status of wireless technologies for multi-hop networks (see Section 2), we discuss the open research challenges in mobile ad hoc networking paradigms: mesh networks (see Section 3), opportunistic networking (see Section 4), vehicular networks (see Section 5) and sensor networks (see Section 6). Section 7 is devoted to the emerging people-centric paradigm that, thanks to the increasing diffusion of the smartphones, combines wireless communications and sensor networks to build computing and communication solutions that are tightly coupled with the daily life and behaviors of people.

2. Technologies for mobile multi-hop wireless networks, [2]

Many technologies and standards, enabling multi-hop wireless networking, as well as off-the-shelf equipment implementing such technologies, are available today [8]. Nevertheless, we can easily foresee that research interest in these topics will not diminish in the next years, but rather it is likely to grow. There are at least two reasons for this.

On the one hand, the development and availability of technologies and equipment is driven by standardization and regulation activities. Networking standards, thus including multi-hop wireless ones, are primarily concerned with ensuring device interoperability, a key requirement to allow for networking equipment mass production and market diversification. Nevertheless, guaranteeing interoperability does not require a full system specification; rather, standards usually do not specify key aspects that do not affect interoperability to create additional space for competition among manufacturers. One such example is the resource allocation/scheduling on the data plane, whose implementation strongly affects performance but does not concern interoperability. Therefore, new technologies and standards, even though leaning upon a layer of fundamental research results, always call for investigating many practical aspects that are mainly related to system customization and performance optimization in concrete scenarios. In the following sections, we will highlight the challenges that we envision for a set of relevant technologies and standards related to wireless multi-hop networks.

On the other hand, one key advantage of mobile multi-hop/mesh wireless communication technologies is that they allow for easy and fast, highly scalable and cost-effective network deployment under heterogeneous environments. Therefore, there are many heterogeneous application scenarios where multi-hop wireless technologies represent one of the most effective solutions, if not the only viable one. Many of such scenarios are real today, like public city-wide dedicated services (e.g., video-surveillance or transport systems), Internet access in rural areas, environmental monitoring through sensing systems, disaster emergencies, etc. As observed in [4], a pragmatic development approach allowed a bunch of research activities to thrive focusing on the specific challenges and requirements of these different scenarios in order to build robust and effective networking solutions (either mesh, sensor, opportunistic, or vehicular). We think however that new application and deployment scenarios, for which multi-hop wireless networks can play a crucial role, will just grow exponentially in the near future, as the *Internet of Things* vision will become a reality [9]. Connecting everything, anytime and everywhere will demand for capillary and pervasive network coverage, for which multi-hop wireless technologies represent an effective solution. However, such scenarios will pose many new challenges – one on top of all others: scalability – which will entail reconsidering current results and will likely boost a new wave of research on multi-hop wireless technologies. Let us briefly review some of them in the following.

Smart cities. This term identifies a generic scenario where *Information and Communication Technologies* are employed to sustain the development of urban environments. This is achieved by the pervasive deployment of sensing, computation, and communication infrastructures in order to collect and distribute the information needed to develop and improve new services offered to citizens by municipalities. As such, this scenario is indeed comprehensive of many heterogeneous ones. In most cases, the communication infrastructure is characterized by frequent topology changes, faults in equipment, and/or harsh environmental conditions, which naturally call for the use of multi-hop wireless network technologies. All scenarios, however, share some common and unique features, e.g., very dense networks comprising thousands of devices, and uncommon traffic patterns made of a very large number of low data-rate flows. As highlighted in [10], this needs reconsidering traditional network design and technologies, and open new challenges in terms of standardization (including multi-hop communication), cooperation (e.g., managing interference in dense environments), security, QoS [11], etc. Research activities addressing these new challenges are already ongoing, and more are expected to come, as the Smart City scenario will evolve in the future.

Industrial Internet. Communication networks are a key component of infrastructures supporting complex industrial processes. Being involved in the control process, they have very critical requirements in terms of reliability and QoS [12]. To meet such requirements, industrial networks typically use wired connections, and dedicated standards have been developed. On the other hand, the need to reduce costs is triggering a new trend towards IP-based solutions that

[1] For example, since 2013, only one paper with the keyword "MANET", in the title, has been published in *Computer Communications*. Furthermore, only a few papers, focusing on MANET issues, have been published in this journal in the last three years.

[2] By Enzo Mingozzi.