
**MOBILEMAN**

IST-2001-38113

Mobile Metropolitan Ad hoc Networks

# MOBILEMAN

# Final Report

Deliverable D20

Draft Version for Review meeting only

Starting date: 1 October, 2002

Duration: 39 months

Contractual Report Preparation Date: 31 December, 2005
Actual Date of Delivery: TBD, 2006
Estimated Person Months: 1.5
Number of pages: 46
Classification: Internal circulation within project

***Contributing Partners***: Consiglio Nazionale delle Ricerche (Italy), University of Cambridge (UK), Institut Eurecom (France), Helsinki University of Technolgy (Finland), NETikos (Italy), Scuola Universitaria Professionale della Svizzera Italiana (Switzerland)

***Authors***: Marco Conti, (CNR);

***Abstract***: This deliverable provides a comprehensive view of the results obtained, the methodologies and approaches employed, changes in the state-of-the-art since the project was contracted. Specifically we elaborate on the degree to which the project objectives have been reached. In addition we also discuss the socio-economic impact of the project.


**Project funded by the European Community under the "Information Society Technologies" Programme (1998-2002)**

## Summary

MOBILEMAN (http://cnd.iit.cnr.it/mobileMAN) is a project funded by the Future and Emerging Technologies arm of the IST Programme of the the European Commission.

MOBILEMAN aimed to explore the technical, social, and market effectiveness of the ad hoc networking paradigm at the European level by overcoming the barriers that could negatively affect the significance of results obtained at the national level; thus producing a common European approach toward self-organized networks to balance the USA leadership in this area. To achieve this, we set up a consortium consisting of partners whose role and competence could fill the complete chain of scientific and technological skills required to realize a metropolitan area, self-organizing, and totally wireless network named *Mobile Metropolitan Ad hoc Network* (MobileMAN). Specifically, we planned to investigate a MobileMAN from three perspectives: *Technical, Social,* and *Economic.* The investigation of the Social and Economic aspects was under the responsibility of SUPSI-DSAS and University of Cambridge, respectively. Technical activities were subdivided among all partners. As indicated in Deliverable D2, CNR and SUPSI-DTI had the responsibility for the design and implementation of the novel MAC card, respectively. In addition, CNR cooperated with Cambridge University for middleware platforms, and coordinated the testing/experimenting activities. HUT was mainly in charge of developing and testing the mobile ad hoc network following a legacy, layered architecture. Eurecom had the responsibility for all security and cooperation issues. Applications have been Netikos main responsibility.

According to the original objectives this project aimed to defining and developing a metropolitan area, self-organizing, and totally wireless network. However, experimental results produced during the first year of the project clearly indicated that a metropolitan-scale is not realistic with the current technology; hence the project objectives were re-tuned to study more realistic campus-wide multi-hop ad hoc networks.

The outputs of the project can be summarized as follows. i) Development, validation, implementation and testing of the architecture, and related protocols, for configuring and managing a MobileMAN; ii) physical implementation of this architecture for lower layers (i.e., wireless technologies); iii) integration of applications on top of our self-organized network; iv) validation of the self-organizing paradigm from the social and economic standpoint.

# Table of Contents

# 1. INTRODUCTION

MOBILEMAN (http://cnd.iit.cnr.it/mobileMAN) is a project funded by the European Commission under the Future and Emerging Technologies arm of the "Information Society Technologies" Programme aimed at investigating the potentialities of the self-organizing networking paradigm for building future communication systems. Indeed, there is a significant expectation that future communication systems will heavily rely on wireless technologies. At the end of nineties, the proliferation of mobile computing and communication devices (e.g., cell phones, laptops, handheld digital devices, personal digital assistants, or wearable computers) fueled the explosive growth of mobile computing equipment market. According to a study by Cahners In-Stat Group, the number of subscribers to wireless data services were expected to grow rapidly from 170 million worldwide in 2000 to more than 1.3 billion in 2004. Among all the applications and services run by mobile devices, network connections and corresponding data services were the most demanded service by the mobile users. 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 require 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. Given this scenario, the alternative infrastructure-less networking paradigm started to be investigated. These are focused around having the mobile devices connect to each other in the transmission range through automatic configuration, setting up an ad hoc mobile network that is both flexible and powerful. In this way, not only can mobile nodes communicate with each other, but can also receive Internet services through Internet gateway node, effectively extending Internet services to the non-infrastructure area. Therefore, infrastructure-less networks were (and are) expected to become an important part of the 4G wireless and mobile networks architecture.

In infrastructure-less networks, *the users' mobile devices are the network*, and they must cooperatively provide the functionalities that are usually provided by the network infrastructure (e.g. routers, switches, servers). 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. Such systems are sometimes referred to as Mobile Ad hoc NETworks (MANET's), or as self-organizing networks.

Mobile Ad hoc Networks immediately gained momentum because they make possible realizing network services for mobile users in areas with no pre-existing communications infrastructure, or when the use of such infrastructure requires wireless extension. Ad hoc nodes can also be connected to a fixed backbone network through a dedicated gateway device. This brings IP network services to mobile users without requiring any pre-installed infrastructure. All these advantages make ad hoc networking an attractive option in future wireless networks.

The MOBILEMAN project proposal started from the observation that, at the beginning of year 2000, while Europe has established world-renowned leadership in infrastructure-based mobile communications, through research and industrial efforts, the European

research on self-organizing network was at an early stage. At that time, USA were driving research in this area, mainly in the context of defense-related projects, while in Europe, research was mainly performed by research groups operating at the national level. The aim of the MobileMAN project was therefore to constitute a kernel of European research on self-organizing networks, and to reduce the gap between Europe and USA. Specifically, the project aimed to define and develop a metropolitan area, self-organizing, and totally wireless network that we called *Mobile Metropolitan Ad hoc Network* (MobileMAN).

A MobileMAN is an autonomous, self-organized, wireless multimedia network, built up solely from user devices. In a MobileMAN, no infrastructure is required to enable information exchange among users. User devices are goods that people can purchase at (relatively) low cost, and operate without per-use service fees. The only external resource needed for operation is the bandwidth in the (unlicensed) ISM band. In a MobileMAN, nearby terminals can communicate directly. Terminals that are not directly connected communicate by forwarding their traffic via a sequence of intermediate terminals. No specialized devices (such as Internet routers or cellular towers) are required. In addition to connectivity, the terminals of a MobileMAN must also cooperatively provide the services -- naming, security, service discovery, data replication -- needed to support applications used in the MobileMAN network. A MobileMAN is not intended as a replacement for current infrastructure based (wired and wireless) networks. It is intended to complement them, and to enable new application scenarios in which a centralized infrastructure is impossible, undesirable, or unnecessary. Indeed, we also envisaged integration between a MobileMAN and the Internet. Application supported by a MobileMAN might range from text messaging systems (evolving from the very popular SMS), up to more demanding multimedia (voice and video) services.

This deliverable first presents the project objectives and discusses changes in the state-of-the-art since the project was contracted. Then it provides a comprehensive view of the results obtained, the methodologies and approaches employed. In addition we also discuss the impact of the project.

# 2. PROJECT OBJECTIVES

According to the original project objectives this project aimed to defining and developing a metropolitan area, self-organizing, and totally wireless network that we called *Mobile Metropolitan Ad hoc Network* (MobileMAN). Specifically, the **objectives** of this project were:

- **technical solutions**: invent and demonstrate solutions that make the self-organisation paradigm effective. This will be reflected into developing the architecture and protocols for a self-organised network, integrated with the lower and upper layers.

- **business and social impact**: to exploit the self-organization paradigm for supporting innovative applications (in terms of novelty of the services context onto which the applications are integrated, and novelty of the way they are offered to the users), which will improve the life quality of people.

To achieve these main objectives the project identified a set of relevant results (both from a technical and socio-economic perspective) to be achieved. Specifically, the main expected **technical outputs** of the project included:

- The development, and validation of effective solutions for the relevant technical issues of self-organizing networks: routing and forwarding, services' location, medium access control protocols, middleware, security and cooperation.
- The hardware/software implementation of the above solutions.
- The integration of the developed solutions in a fully functioning testbed. Integration and validation of popular services (such as messaging and chatting) on top of our self-organized network, as well as, the extensions of these services into new realms, such as multimedia messaging, spontaneous electronic collaboration, and wireless interactive games.
- Testing the MobileMAN prototype in a large-scale testbed.

The main *business and social outputs* of this proposal were summarized as follows:

- Evaluation of the social impact of the self-organizing paradigm by exploiting virtual communities of real users.

- A socio-economic evaluation of the effectiveness of the mobile ad hoc paradigm, and its market access.

It is worth noting that, being mobile ad hoc networking a very dynamic research area, during the project activities new challenges were identified. Among these, it is worth remembering a novel organization of a MobileMAN architecture by exploiting the cross-layer principle. The potentialities of this new approach emerged during the project first year and, to explore them, new objectives were added to the project to show, through proof-of-concept prototypes and via simulation, the benefits of the cross layer approach. More precisely, the new objectives we identified included:

- To define a cross-layer architecture and protocols for a MobileMAN.
- To develop a testbed for experimenting the benefits of a cross-layer architecture.
- To develop a simulation framework to study the cross-layer architecture on a larger scale with respect to the experimental testbed.

# 3. METHODOLOGIES

The MOBILEMAN project tried to concentrate on novel concepts required to achieve the project goals, avoiding the not-invented-here attitude. Therefore, the first step of the project was an in-depth critical review of the extensive literature in the field (see footnote 1) and an analysis of European projects related to MobileMAN objectives (see footnote 2). From these careful analyses we identified:

- the need for an *Implementation/Integration/Experimentation* approach in MANET design;
- the need for a pragmatic and realistic approach in MANET design;
- the emerging of a novel approach in the designing the mobile ad-hoc network architectures based on the cross-layering principle;
- a top-down approach to MANET.

## *3.1.* Implementation, Integration, Experimentation

The analysis of the extensive literature on MANETs (when the project started the related literature counted more than 2000 papers) pointed out that ad hoc networking was (is) not yet a consolidated field. MANET (Mobile Ad Hoc NETworks) IETF task force since 1997 is working to develop Internet routing for multi-hop ad hoc wireless networks. Four major candidates routing protocols (AODV and DSR, OLSR and TBRPF) have been identified but there is lack of convergence. There has been good progress in studying the protocols' behavior (almost exclusively by simulation), but the absence of performance data in on-field trials and in non-trivial network configurations continued to be a major problem. More than 10 years of research were carried out but the area was far from being consolidated. Indeed the focus of MANET research was mostly on revising routing Internet drafts. In addition, main other areas were analyzed (and new areas continuously added). However, most works focused on either a single layer/issue (MAC, Routing, TCP, middleware, etc.), or analyze the interaction among few layers (e.g., TCP and MAC, TCP and routing, energy and topology control). There was a lack of an overall view of MANET architecture and protocols and of a clear understanding of how MANETS work in reality. Specifically, we identified three areas where lack of "realism" was critical: i) *Integration* (lack of), ii) *Implementations/Testbeds* (lack of), and iii) *Experimentation* (lack of).

---

1 I. Chlamtac, M. Conti, J. Liu, "Mobile Ad hoc Networking: Imperatives and Challenges", *Ad Hoc Network* Journal, Vol.1 N.1 January-February-March, 2003.
S. Basagni, M. Conti, S. Giordano, I. Stojmenovic (Editors), *Mobile Ad hoc networking*, IEEE Press and John Wiley and Sons, Inc., New York, 2004.

2 Organization of the ESF/PESC Exploratory Workshop "*Is Mobile Ad hoc Networking part of the future of mobile networking in Europe*?" (October 2002), and the projects session within the 8th IFIP-TC6 Conference on *Personal Wireless Communications* (September 2003).

The ad hoc protocols (and Internet drafts) production cycle was/is mainly driven by simulation. The approach was (and still mainly is): "implementations can come later, simulations tell the truth".
Very few attempts existed in the literature to validate/calibrate simulative studies with measurements. In addition, not all aspects of a real ad hoc network were represented in simulative models (e.g., most simulators assumed the same transmission range for *unicast* and *broadcast* frames).

Given this status of the art in the MANET research, the MobileMAN project was tuned to tackle the lack of Integration, Experimentation and Implementations/Testbeds. Specifically, the project focused on the development and validation of solutions for the relevant technical issues of self-organizing networks (routing and medium access control protocols, power management, security, and location), and the implementation of integrated solutions. The aim was to concentrate the project efforts on novel and unsolved issues. Real testbeds have been used in MobileMAN either to validate the developed solutions whenever possible or, (at least), to calibrate/validate the simulation models to be used for architecture and protocols design. Furthermore, whenever possible, hardware/software implementation of the MobileMAN solutions have been developed and integrated in our testbeds.

## 3.2. Realistic and Pragmatic Approach

The analysis of the literature pointed out that a large portion of protocols' development is done in simulation settings only -- often considering unrealistic scenarios, e.g., 1000-node scenarios with CBR traffic -- while clear results showing how well MANETs work in reality were almost missing. To reduce the gap between what end users might find useful and what research was currently addressing, a pragmatic research approach focusing on the realization of **realistic small/medium scale mobile ad hoc networks** was needed. Realistic means focusing on case studies relevant for the users. A scenario consisting of a few people wanting to form an ad hoc network and sharing access to the Internet is simple, but much more probable and feasible. Small scale is dependent on the technology. For the current 802.11 technology it has been identified an *ad hoc horizon* at two to three hops and 10 to 20 nodes where the benefits from wireless multihop ad hoc networking virtually vanishes. The focus should therefore be to get the most out of ad hoc networking *within* these limits.

From this observations, we defined a pragmatic research approach for MobileMAN based on realization and testing of solutions for realistic small/medium scale networks. Indeed in the project, we developed, implemented and tested our solutions for campus-wide networks, looking at supporting file and content sharing applications, VoIp applications and guaranteeing the interconnection of ad hoc island with the Internet. In addition, the availability of prototypes made possible to create small communities of MANET users that, by experimenting with this technology, provided feedbacks on its usefulness.

## 3.3. Cross-layer Design

The IETF MANET working group has the main role in standardizing protocols for mobile multi-hop ad hoc network. IETF MANET WG proposes a view of mobile ad hoc networks as an evolution of the Internet. This mainly implies an IP-centric view of the network, and the use of a layered architecture. In principle, this paradigm greatly simplifies the network design and makes the interconnection of MANETs and the Internet easier. However, during the project first-year activities, we identified limitations of this approach that prevents the development of efficient solutions, which are very important in a resource-constrained environment like a MANET. For this reason, we investigated to what extent the pure layered approach needs to be modified. Two main directions, both with pros and cons, were analyzed: i) extension of the layered architecture by adding layer triggers; and ii) a full cross layering design exploiting cross-layer interaction among all layers. The first approach limits the interactions to adjacent layers only, thus making possible only limited optimization. On the other hand, relaxing as much as possible the Internet layered architecture, by removing strict layer boundaries, is highly desirable from a performance standpoint but may violate the layers independence principle which is one of the key elements of the worldwide diffusion of the Internet (see footnote 3).

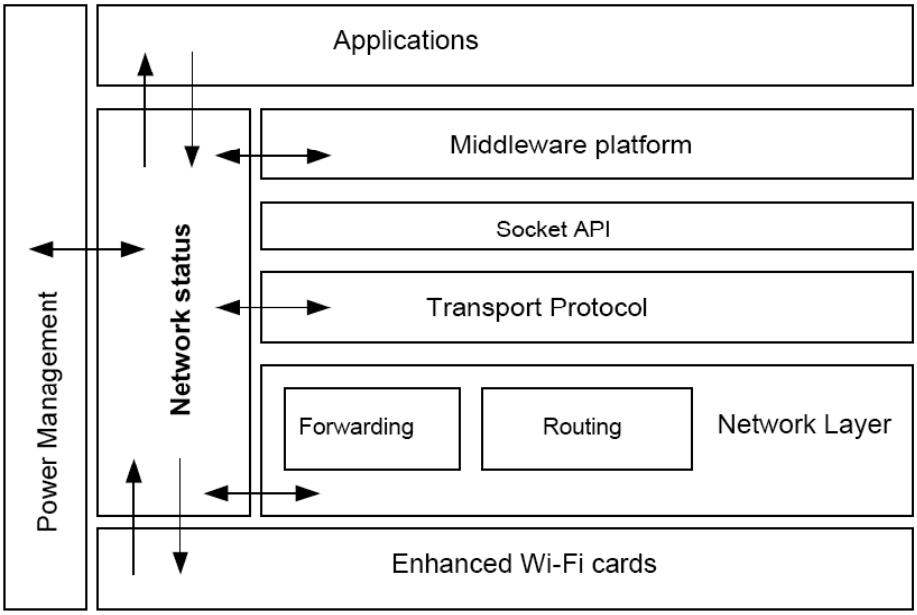


**Figure 1. NeSt Architecture**

By comparing and contrasting the opposite research directions we elaborated the MobileMAN solution to the problem: introducing cross-layer interactions among layers, still maintaining a layered organization and the layer separation principle; this represents a good compromise between the two positions (layer triggers vs. un-layered architecture).

[3] V. Kawadia and P. R. Kumar, "A Cautionary Perspective on Cross Layer Design," *IEEE Wireless Communications*, Feb. 2005.

This is made possible by the introduction of a vertical module, called Network Status (NeSt), which controls all cross-layer interactions through data sharing (see Deliverable D13 for details). Specifically, the NeSt supports vertical communications among the layers by acting as a repository for information collected by network protocols, see Figure 1. Each protocol can access the Network Status to share its data with other protocols and interact with them. By standardizing the NeSt interface (which defines how protocols can access/modify shared data) the layer separation principle is preserved. Indeed, in this way, cross-layer interactions do not directly take place between the interested protocols, but are implemented using the abstractions exported by the NeSt, without modifying the interfaces between adjacent layers. Protocols have to implement the NeSt interface to implement cross-layer optimizations but no constraint exists on protocols internal implementation. A protocol can be replaced with a new release without affecting the protocol stack. In addition, using legacy protocols (i.e., no network-status enabled) is still possible although with degraded performance (i.e., without cross-layer optimizations). For example, using the legacy TCP protocol implies that cross-layer optimizations will not occur at this layer and that the transport protocol will not provide any information to the Network Status component. However, the overall protocol stack still operates correctly. The design of a NeSt module from both a functional and an implementation standpoint is discussed in Deliverable D13. The effectiveness of the NeSt-based approach has been extensively evaluated by both simulation and experimental results obtained by implementing a multi-hop ad hoc network prototype (see Deliverable D16).

## 3.4. Top-down Approach

The main research approach used by the MANET research community has been a bottom-up one. Lots of protocols and networking solutions have been proposed to deal with the challenging networking environment, in order to support legacy applications also in MANETs. In this view, MANETs are not seen as an opportunity for applications, but as quite hostile environment for legacy applications to operate in. On the contrary, we envision novel application scenarios that leverage the key MANET features in order to provide value to the end user. The required networking solutions come in a second stage, in order to address the real needs of these scenarios. Such a top-down approach has been often neglected by the research community, while we believe that it represents a key avenue to successfully bring MANET technologies into the market.

# 4. PROJECT RESULTS

As explained in the previous section, the MOBILEMAN project aimed at creating an European perspective on self-organizing networking to contrast the USA leadership in this field by developing novel methods, tools, algorithms, and protocols supporting the construction and provisioning of self-organizing systems and applications. Alongside this, there are methods and tools specifically tailored for evaluating the economic and social impact of this technology. Hereafter, by reviewing the main results produced by the project, we will show that all these objectives have been achieved.

## *4.1. Technical Results*

Contributing to increasing the visibility of the European research in the field would be not possible without carrying out high-quality research able to produce significant contributions to the scientific literature. Specifically, after a careful analysis of the state of the art, the project activities concentrated on three areas where significant contributions were still needed: i) *Integration*, ii) *Implementations/Testbeds*, and iii) *Experimentation*. Indeed, MobileMAN researchers produced relevant results in:

i) Design, validation and implementation of architecture and protocols for mobile ad hoc networks.
ii) Integration of our results in prototypes used for extensive experimentations.

### 4.1.1. Design validation and implementation of architecture and protocols for mobile ad hoc networks

In this section we summarize the main results of the project related to the design and validation of the architecture and protocols (from the medium-access-control to the application layer). After analyzing the novelty of our approach in designing the architecture of mobile ad hoc networks, we present the main results in protocols design. The presentation follows a bottom up approach: from wireless technologies up to applications.

MOBILEMAN ARCHITECTURE

One of the main project results has been the introduction of the cross-layer principle in mobile-ad-hoc-network organization still maintaining a layered organization of the network architecture and the compliance with TCP/IP protocol stack. More precisely, the MobileMAN cross-layer architecture is based on a layered organization, which can be enhanced with cross layering interactions if information gathered at different layers of the network stack is shared in a common local memory structure (Network Status, referred to as *NeSt*). Specifically,

- the *NeSt*, which is the key of the cross-layer architecture, has been completely defined by specifying the NeSt interaction models, and its exported interfaces.

- We designed the software architecture of a NeSt prototype supporting cross-layer interactions between a proactive routing protocol and the middleware platform, CrossROAD, which has been developed during the project.

- Starting from the software architecture, we implemented a proof-of-concept prototype of our cross-layer architecture.

- An experimental phase provided a proof of the benefits of this new approach in MANET design.

- A special attention was devoted to study the performance of our cross-layer architecture. To this end we extended the Network Simulator NS-2 (v. 2.27) with a cross-layer interface (XL-interface) that standardizes vertical interactions among protocols according to the MobileMAN cross-layer architecture.

WIRELESS NETWORKS

- Analysis of the limits of the existing solutions based on IEEE 802.11 for constructing multi-hop ad hoc networks. The analysis has been performed by simulation and measurements.

- Definition of a channel model for CSMA-based wireless networks to be used for protocols design and to tune simulation models. The model is suitable for both 802.11 networks and Mote-based sensor networks.

- Design of an enhanced MAC protocol (AOB) for ad hoc networks. The new MAC protocol is compatible with the IEEE 802.11 and provides a better channel utilization.

- Extension of the AOB mechanism, with a credit-based mechanism, to effectively operate in a heterogeneous environment where enhanced and legacy cards co-exist.
  - The credit mechanism provides a formal basis to the activities of TG 802.11n that is working toward higher throughput for 802.11 networks. Indeed, AOB extended with the credit mechanism provides an optimized and efficient solution to the multiple transmissions approach currently under study in TGn.
  - It provides an efficient solution to fix 802.11 unfairness in multi-hop scenarios.

- Hardware implementation of the enhanced MAC card implementing both the AOB mechanism and its credit-based extension.

- Experimental validation of the AOB mechanism on a 4-node testbed.

- Implementation in the NS-2 tool of the simulation model of the enhanced MAC card.

- Validation of the AOB mechanism via simulation on large-scale networks.

NETWORKING PROTOCOLS

- Design and evaluation of a packet-forwarding scheme (REEF) for the reliable data forwarding in mobile ad hoc networks.
- NS-2 implementation of the REEF model.
- Design and implementation of the Ad Hoc routing framework software package for nodes (PDA or Laptop) running the Linux Operating System. The Ad Hoc routing framework supports different ad hoc routing protocols: proactive (OLSR), reactive (AODV) and also some hybrid solutions.
- Design and implementation of a Service Discovery Module (SDM). SDM provides the basic functionalities to implement (in an efficient way by exploiting cross layering) at the middleware layer the discovery of any service.
- Design of an architecture that allows constructing a *hybrid network environment* to interconnect (islands of) multi-hop ad hoc networks to the Internet.
- Implementation of the *Ad Hoc Proxy ARP daemon* (*AHPAd*) that enables the interconnection of MobileMAN ad-hoc islands to the Internet.
- Design and evaluation of a transport protocol for ad hoc networks (TPA)
- NS-2 implementation of the TPA.
- Prototype implementation of TPA

CO-OPERATION MODELS AND MECHANISMS

- Design of a model that allows studying the cooperation in mobile ad hoc networks.
- Design of the *Cooperation enforcement mechanism* (CORE) that encourages users to behave as "good citizens".
- Validation of the CORE mechanism. By exploiting a non-cooperative game model we showed the effectiveness of the CORE mechanisms with respect to other policies proposed in the literature.
- Implementation of CORE for the Linux operating system. CORE has been implemented as a Linux daemon. CORE software architecture includes three building blocks: a) a MAC layer sniffer that monitors the packets; b) a reputation function; c) a punishment mechanism.
- Experimental validation of CORE on a small-scale testbed.

- Large-scale validation of CORE by simulation. CORE has been implemented as an add-on component for the Glomosim network simulation suite.

MIDDLEWARE

- Development of NS-2 simulation models for p2p structured (Pastry) and un-structured (Gnutella) platforms;
- Simulation study of Pastry and Gnutella platforms in multi hop ad hoc networks;
- Integration of a free implementation of Pastry (FreePastry) in the MobileMAN architecture.
- A new middleware (CrossRoad) for ad hoc networks was designed and developed. It optimizes the Pastry platform by exploiting cross layer interactions with the network layer.
- A cross-layer optimization of Gnutella (XL-Gnutella) was designed and implemented in the NS-2 framework.
- Simulation comparison of Gnutella and XL-Gnutella showed that XL-Gnutella outperforms Gnutella in mobile ad hoc networks.

NEW APPLICATIONS AND SERVICES

We developed and integrated in the MobileMAN software architecture co-operative tools for document/content sharing based on a P2P architecture (Whiteboard and UDDI); and a VoIp application, which exploits the legacy TCP/IP protocol stack. Specifically, the following software modules have been developed:

- A Whiteboard application (implemented in Java) to create a virtual group (a community) for a limited amount of time in order to exchange dynamically generated content (e.g., drawings and text). The whiteboard application is a p2p multicast application which exploit the services offered by any structured overlay network implementing the commonAPI interface.
- *UDDI for manets (UDDI4m)*: a service discovery and location protocol for MANETs called *UDDI for manets (UDDI4m)*. This protocol exploits the traditional UDDI protocol with the introduction of a level that allows fitting into ad hoc environment.
- The VoIP application included in the Ad Hoc framework contains two main modules; signaling module and data transport module. The signaling module implements the SIP signaling protocol and utilizes IP addresses for finding the peer nodes to initiate the VoIP session; it uses UDP as the transport protocol. The data transport module

implements a RTP client for exchanging the voice packets. A public-source GSM codec is used for encoding audio samples.

### 4.1.2. Integration and experimentation

By exploiting the software we developed, and integrating it with existing software modules, we obtained three (software) architectures to be used for testing MobileMAN ideas. Specifically, we have:

1) a legacy TCP/IP architecture on which we run VoIP applications;
2) a legacy p2p architecture on which we run both Whiteboard and UDDI4m applications
3) a p2p cross-layer architecture on which we run both Whiteboard and UDDI4m applications

By exploiting these architectures, we implemented small- and medium-scale ad hoc networks on which we performed extensive experimental evaluations, that contributed to remove a set of simplifying assumptions commonly used in simulative studies that caused a lack of credibility in most of the results so far obtained. Specifically, it is worth remembering:

- the testing of 802.11 multi-hop ad hoc networks;
- the comparison of proactive (OLSR) and reactive (AODV) routing protocols on realistic testbeds;
- the measurement-based analysis of FreePastry and CrossROAD performance when running on mobile ad hoc networks;
- the experimentation of a medium size (up to 23 nodes with paths made up of up top 8 hops) ad hoc network implementing the architectures 1 and 2. Currently, this is one of the largest ad hoc testbeds implemented in worldwide research projects.

## *4.2. Socio-economic Results*

### 4.2.1. Social Evaluation

We applied the participatory design approach to involve potential end-users in evaluating how they perceive the MobileMAN technology and how to integrate it into their life. Several categories of users were involved in the social evaluation, e.g., students, professionals, businessmen, elderly.

The main result of social evaluation is apparently a negative one. Indeed, due to the perceived abstract nature of ad hoc networks, users have huge difficulties in seeing the aspects that are specific features of ad hoc networks. For this reason, even though several different communities of users were involved in the social analysis (among others, university students, businessmen and elderly), and different methodologies and tools have been applied (from web-based tools like wiki and blogs, up to questionnaires and interviews), the social studies were not able to identify novel scenarios for MobileMAN usage. This negative result, it is not completely negative for our project. Indeed this indicates that the pragmatic approach of the MobileMAN project, which focuses the research on developing and implementing prototypes in realistic scenarios (small scale networks with legacy applications), is the correct one to lowering the barriers for the users' access to ad hoc networking. On the other hand research based only on simulation studies of very large node scenarios (up to 1000 nodes) with CBR traffic (as it is done by most of the research in the field) does not provide any contribution to create the conditions for motivating the users to find this technology useful.

### 4.2.2. Economic and Market Access

The area of ad hoc networking is of long-term nature. However, our results show good potentialities from the innovation and economic standpoint. Specifically, We have identified new applications that can leverage the ad hoc technology to provide valuable services to the user. The city cab scenario (i.e., the use of 802.11 ad hoc networks to replace the currently used taxi radio dispatch systems) is the most promising one. We have found that, in this scenario, an ad hoc networking system is viable both economically and technically.

In addition, for our market analysis of ad hoc networking technologies we highlighted that mesh networks constitute a short-term direction to turn mobile ad hoc networks in a commodity by providing a flexible and "low cost" extension of wired infrastructure networks.

# 5. DELIVERABLES AND REFERENCES

Project deliverables constitute the primary way to disseminate the project results. All project Deliverables are available as public material on the project web site: http://cnd.iit.cnr.it/mobileMAN. Hereafter the main project deliverables are briefly summarized. We also report a comprehensive table of deliverables attached. Other references like articles, conference presentations are also be listed.

## *5.1. Public Deliverables*

The MobileMAN deliverables address the several project objectives; specifically we can group them, as follows:

a. *MobileMAN architecture and protocol design*: Deliverables D5 (MobileMAN architecture, protocols, and services - first report), D10 (MobileMAN architecture, protocols, and services – intermediate report), and D13 (MobileMAN domain modelling);

b. *Hardware and software implementation of MobileMAN solutions*: Deliverables D6 (MobileMAN functionalities – a minimal set), D11 (MobileMAN functionalities – enhanced set), D12 (MobileMAN Wireless Network Interface), and D14 (MobileMAN functionalities – final set)

c. MobileMAN architecture and protocol validation and experimentation: Deliverables D8 (MobileMAN first phase) and D16 (MobileMAN technical evaluation).

d. MobileMAN social evaluation: Deliverables D7 (Socio-economic research methodology), and D17 (Socio-economic evaluation)

e. MobileMAN economic evaluation and market access: Deliverable D18 (Economic value of self-organisation paradigm and market access).

In addition to these are the deliverables related to:

*MobileMAN dissemination and exploitation*: Deliverable D1 (Project web site), Deliverable D3 (Dissemination and Use Plan), Deliverable D15 (MobileMAN Presentation - workshop), and Deliverable D19 (Exploitation plan)

*MobileMAN project planning and self-evaluation*: Deliverable D2 (Project Plans), Deliverable D4 (MobileMAN intermediate evaluation report), Deliverable D9 (MobileMAN intermediate evaluation report) and Deliverable D20 (Final Project Report).

The complete list of deliverables is reported in Tables 1a-1d.

Hereafter, we report a brief description of Deliverables a.-e. above

### 5.1.1. MobileMAN architecture, protocols, and services

The deliverables in this set presents the design and analysis of the MobileMAN architecture and protocols (from the medium access control to the application layer). Deliverable D13 is the third document in a series (D5, D10 and D13) and is devoted to present the consolidated MobileMAN architecture and protocols. To make reading easier, D13 is a self-contained presentation of MobileMAN architecture and protocols. The presentation follows a bottom up approach from wireless technologies up to application and economic issues. When appropriate, the social and economic perspectives are also used to compare and contrast technical solutions.

The MobileMAN architecture supporting cross-layer interactions is presented in Section 1. In this section we focus on the specification of the Network Status (NeSt) which is a node local memory where information gathered at different layers of the network stack is shared among different protocols and used to adapt the behavior of the node depending on the particular circumstance (e.g., traffic type, channel perturbations, network status, node selfishness and/or maliciousness, among the others) the node operates in. Section 2 discusses the problems when using 802.11 cards in multi-hop ad hoc networks and the enhanced card we designed and implemented to solve these problems. The description of the enhanced card has been presented in Deliverable D12. Section 3 is devoted to presenting MobileMAN networking protocols that use the one-hop transmission services provided by the network interface card to construct end-to-end (reliable) delivery services. The basic functionalities implemented by these protocols include routing and forwarding algorithms to deliver the information through the MANET. In addition the low reliability of communications (due to wireless communications, users' mobility, etc.), and the possibility of network congestion require a transport protocol tuned for the MANET environment. Last, to efficiently support cross-layer interactions the routing algorithms have to be extended to support a *location service* to discover the nodes in the network that are offering a specified service. All these functionalities and protocols were already specified in D5 and D10. The new material presented in D13 is related to the validation of the transport protocol mechanisms we developed (see the TPA protocol in Deliverable D5). This validation, performed via simulation, shows that TPA outperforms legacy TCP protocol in all operating conditions we investigated. Section 4 addresses the enforcement of cooperation within a MANET. The deliverable proposes an approach that analyzes the implications of the lack of cooperation in a peer-to-peer network together with a sociological study of cooperation models. Section 5 deals with the MobileMAN middleware platforms. Firstly, we present the Pastry platform that was identified in Deliverable D5 as the most interesting middleware platform (among existing p2p platforms) for a MobileMAN network. Then, we introduce and describe *CrossROAD*: *CROSS-layer Ring Overlay for AD hoc networks*. CrossROAD is our proposal to enhance Pastry by exploiting cross-layer interactions. The new material we present in D13 is the detailed description of the CrossROAD software architecture. In Section 6 we present the three applications we

selected to test the MobileMAN architecture: UDDI, a whiteboard application (WB) and a VoIP session.

### 5.1.2. Hardware and software implementation of MobileMAN solutions

The new MAC card we have designed and developed for enhancing 802.11 behavior in ad hoc networks is presented in Deliverable D12. This report describes the system composed of 5 parts (modem, voltage adaptor, DSP board, host PC, power supply) that constitutes an experimental and demonstration bench for the enhanced 802.11 MAC card as specified in the MobileMAN project. The Wireless Network Interface systems (4 of them have been until now manufactured) are physically located at the SUPSI campus, in Manno, (Switzerland) where they are available for demonstrations.

The higher layer of the MobileMAN have been implemented in software on the Linux operating system. Deliverables D6, D11 and D14 present, in an incremental way, the software modules we have developed. for building a MobileMAN, Specifically, Deliverables D14 includes all the software modules required to set up a campus-wide MobileMAN, as identified in D13. Indeed, by integrating the software modules we developed with existing code, we obtained a set of software architectures that enable us to test MobileMAN concepts and ideas. Specifically, we have: i) a legacy (layered) TCP/IP architecture on which we run a VoIP application; ii) a legacy (layered) p2p architecture on which we run Whiteboard and UDDI4m applications, and iii) a p2p cross-layer architecture on which we run both Whiteboard and UDDI4m applications. In addition, in D14, we also present our solution to interconnect MobileMAN ad hoc islands among themselves and with the Internet by implementing an *Ad Hoc Proxy ARP daemon* (*AHPAd*).

The software modules are also made available in the Software web site http://keskus.hut.fi/tutkimus/MobileMan.

### 5.1.3. MobileMAN architecture and protocol validation and experimentation

There are two main approaches in system evaluation: measurements on real testbeds and analytical/simulation modeling. Whenever possible we constructed small- medium-scale testbeds to validate our solutions by taking into consideration real scenarios. Modeling studies have been extensively used in the protocols' design phase, and to study the MobileMAN system behavior in complex scenarios that are very difficult (if not impossible) to be studied by prototypes. In the latter case, to develop and solve our simulation models we used simulation tools.

Two main experimental phase have been carried out as documented in Deliverables D8 (first phase) and D16 (second phase). In Deliverable D8 we present the results obtained from an extensive experimental study performed by setting up a preliminary prototype of a multi-hop

ad hoc network, and testing its performance on a small-scale ad hoc network (up to 12 nodes). During the first phase the experimental results focused on analyzing the MAC and routing protocols behavior. The second phase was devoted to present the validation results of the architecture, protocols and services designed for the MobileMAN project. D16 therefore represents the complement of Deliverable D13.

In Deliverable D16, whenever possible, our evaluations are based on measurements from real small- medium-size testbeds. In addition, simulation results are used to study large scale networks and/or complex mobility scenarios. Results are presented by following a bottom up approach from wireless technologies up to the applications. In this deliverable we considered both legacy layered architectures and the MobileMAN cross-layer architecture. The deliverable follows a bottom up approach from wireless technologies up to the applications. The deliverables ends with a section reporting the experimental evaluation of a MobileMAN medium-size mobile-ad-hoc network (up to 22 nodes) which integrates the solution we have developed.

Specifically, in Section 1, after discussing the performance modeling techniques, we present the characteristics of the simulation framework, which extends the Network Simulator NS-2 (v. 2.27) with a cross-layer interface (XL-interface) that standardizes vertical interactions among protocols according to the MobileMAN cross-layer architecture. This simulation framework has been used in successive sections to validate our cross-layer solutions (e.g., see *Reliable Forwarding* and cross-layer optimization of the *Gnutella protocol*).

In Section 2 we analyze and compare the performance (in multi-hop ad hoc networks) of 802.11 card with those of the enhanced card we designed and implemented. First we present a simulation study that shows the effectiveness of our solutions in several scenarios that (in the literature) are known as critical for 802.11 cards. Then we present experimental results obtained in a 4-node networks. In this network the nodes use either the 802.11 card or our enhanced card. Experimental results confirm previous simulation studies. In addition, they point out additional advantages of the enhanced card when used in a real environment with highly variable channel conditions.

Section 3 is devoted to analyzing MobileMAN networking protocols that use the one-hop transmission services provided by the network interface card to construct end-to-end (reliable) delivery services. Specifically, we first present our experimental results related to OLSR and AODV in small scale networks with node mobility. These results complete the study reported in Deliverable D8. Secondly, we report the performance results of our mechanism for reliable forwarding which exploits cross layer interactions (REEF). This study has been performed via simulation by exploiting our extension of the NS-2 environment. The section ends presenting experimental results of our transport protocol, TPA. Experimental results confirm the observations obtained via simulation and reported in Deliverable D13.

Section 4 is devoted to the interconnection of MobileMAN islands to the Internet. Our solutions have been briefly described in Deliverable D14 where we presented the software developed to support the interconnection. For completeness in this deliverable we first present a refined description of our solution and then we report the experimental results that confirm the effectiveness of our approach.

Section 5 addresses the enforcement of cooperation within a MANET. Specifically, the section presents an in depth analysis of CORE, i.e., our mechanism to

address cooperation issues. The features of CORE are analyzed in terms of simulation metrics that we deem relevant to assess the basic properties of a cooperation enforcement mechanism: the energetic cost beard by CORE-enabled nodes and the efficiency of the detection and punishment mechanisms used in CORE. Simulation results are used to understand if and when a mechanism to distribute reputation information could be necessary in order to improve punishment efficiency: reputation distribution is an optional feature of the CORE mechanism and constitutes to discriminate between CORE and other reputation-based cooperation enforcement mechanisms.

Section 6 deals with the MobileMAN middleware platforms. Performance studies are used to show the effectiveness of the cross-layer optimizations. Specifically, we considered two well-known p2p platforms, Gnutella and Pastry, which represent un-structured and structured overlays, respectively. In the case of Gnutella the study has been performed via simulation; while for Pastry, which is part of the MobileMAN architecture, we performed an experimental study. Specifically, in the Pastry case, we present a set of experimental results obtained by comparing in a small testbed the performance of Pastry with those of *CrossROAD*. CrossROAD is our proposal to enhance Pastry by exploiting cross-layer interactions. Both Gnutella and Pastry studies clearly pointed out that cross-layer optimization are mandatory to achieve good performance in a mobile ad hoc network.

In Section 7 we investigate the quality of service experienced by the three applications we selected to test the MobileMAN architecture: UDDI, a whiteboard application (WB) and a VoIP session. In all cases we evaluated the application performance when running on top of a small MobileMAN testbed. In the case of UDDI and WB, we tested both the legacy and cross-layer architecture.

Section 8 concludes the deliverable by investigating the behavior and performance of a medium-scale MobileMAN network made of (up to) 23 nodes.

### 5.1.4. MobileMAN social evaluation

Deliverables D7 (Socio-economic research methodology) and D17 (Socio-economic evaluation) report the main results of the social evaluation of MobileMAN carried out by SUPSI-DSAS. Specifically, D7 analyzes and reviews the participatory design methodology as the basic tool for actively involve potential end-users in the MobileMAN social evaluation. As a results of a pilot test to verify the viability of this approach, the participatory design methodology was refined. In addition other activities were introduce to complement the participatory design (user-oriented website; study of similar technologies; and study of elderly and disabled relationship with information and communication technologies). The results obtained by applying the above methodologies are reported in Deliverable D17. The main result of social evaluation is apparently a negative one. Indeed, due to the perceived abstract nature of ad hoc networks, users have huge difficulties in seeing the aspects that are specific features of ad hoc networks. For this reason, even though several different communities of users were involved in the social analysis (among others, university students, businessman and elderly), and different methodologies and tools have been applied (from web-based tools like wiki and blogs, up to questionnaires and interviews), the social studies were not able to identify

novel scenarios for MobileMAN usage. This negative result, it is not completely negative for our project. Indeed this indicates that the pragmatic approach of the MobileMAN project, which focuses the research on developing and implementing prototypes in realistic scenarios (small scale networks with legacy applications), is the correct one to lowering the barriers for the users' access to ad hoc networking. Only by developing real prototypes and making the users interacting with them it is possible to obtain useful users' feedbacks on the value of mobile ad hoc technologies. A first step in this direction has been performed during the last six months of the project by involving in the social evaluation of MobileMAN the group of students that were also performing the experimental test on the small-medium size (23 nodes) ad hoc networks. This activity is still ongoing in the framework of a Laurea thesis (supervised by CNR and University of Siena – Social Communications department) analyzing the students' expectations about ad hoc networking.

### 5.1.5. MobileMAN economic evaluation and market access

Deliverable D18 (Economic value of self-organisation paradigm and market access) explores the potentialities of Mobile Metropolitan Ad hoc Networks from an economic point of view. In this document we present several scenarios in which the use of MANET technologies is the basis for the development of services valuable for end users, and a cost-effective solution for the service providers. We give examples of how re-engineering existing applications based on the MANET paradigm allows to i) reduce the maintenance costs for the service providers, ii) reduce the entry barriers for new competitors, and thus iii) reduce the costs for end users. Moreover, we present scenarios in which MANETs allow to develop brand-new applications and services. Finally, we discuss further potentialities that arise by extending the MANET paradigm towards two main directions, i.e., mesh networks and opportunistic networking.

Specifically, Section 1 analyses the legacy MANET networking scenario, i.e., a scenario where the MANET is purely infrastructure-less, and no pre-existing infrastructure is used to build the mobile network. Several usage scenarios are presented, and evaluated from a technical/economic point of view. The approach taken in this analysis is original. The main research approach used by the MANET research community has been a bottom-up one. Lots of protocols and networking solutions have been proposed to deal with the challenging networking environment, in order to support legacy applications also in MANETs. In this view, MANETs are not seen as an opportunity for applications, but as quite hostile environment for legacy applications to operate in. On the contrary, we envision novel application scenarios that leverage the key MANET features in order to provide value to the end user. The required networking solutions come in a second stage, in order to address the real needs of these scenarios. Such a top-down approach has been often neglected by the research community, while we believe that it represents a key avenue to successfully bring MANET technologies into the market. Finally, since a key element for evaluating the proposed scenarios is the user mobility pattern, Section 1 also presents realistic models of user mobility.

Section 2 is devoted to analysing the viability of the mesh networks approach which we believe that a very promising direction to address both the MANET scalability and

connection to Internet issues in a cost-effective way. We presnt usage scenarios for Mesh Networks, and surveys both proprietary and open solutions that are being developed in the market. Finally, section 3 focuses on MANET evolution in a longer time frame. We envision opportunistic networking as one of the most intriguing scenarios from this standpoint. In such scenario, each device forwards data in an opportunistic way, i.e., by exploiting any possible contact with other devices. For example, a contact opportunity is represented by two people walking in the same corridor. Their buetooth/wifi enabled mobile phones get in touch and forward data to each other, "hoping" that the other device will carry the information closer to the eventual destination. Clearly, this scenario opens very challenging research directions, and paves the way for new applications, viable from an economic point of view. For example, due to the ever more widespread diffusion of mobile devices, the infrastructure costs of applications based on opportunistic networking could be negligible, if not eliminated at all.

**Table 1a. DELIVERABLES TABLE**

**Project Number:** IST-2001-38113
**Project Acronym:** MOBILEMAN
**Title:** Mobile Metropolitan Ad hoc Networks

| Del. No. | Revision | Title | Type[1] | Classification[2] | Due Date | Issue Date |
|---|---|---|---|---|---|---|
| **D1** | | Project web-site set up | **S** | Pub | December 2002 | December 2002 |
| **D2** | | Project Plans | **R** | Pub | December 2002 | 21 January 2003 |
| **D3** | | Dissemination and Use Plan | **R** | Pub | March 2003 | March 2003 |
| **D4** | | MobileMAN intermediate evaluation report | **R** | Pub | October 2003 | 7 October 2003 |
| **D5** | | MobileMAN architecture, protocols, and services first report | **R** | Pub | October 2003 | 7 October 2003 |

[1] *R: Report; D: Demonstrator; S: Software; W: Workshop; O: Other – Specify in footnote*

[2] *Int.: Internal circulation within project (and Commission Project Officer + reviewers if requested)*
*Rest.: Restricted circulation list (specify in footnote) and Commission SO + reviewers only*
*IST: Circulation within IST Programme participants*

**Table 1b. DELIVERABLES TABLE**

**Project Number:** IST-2001-38113

**Project Acronym:** MOBILEMAN

**Title:** Mobile Metropolitan Ad hoc Networks

| Del. No. | Revision | Title | Type[1] | Classification[2] | Due Date | Issue Date |
|---|---|---|---|---|---|---|
| **D6** | | MobileMAN functionalities – a minimal set | **S** | Pub | October 2003 | November 2003 |
| **D7** | | Socio-economic research methodology | **R** | Pub | March 2004 | 7 April 2004 |
| **D8** | | MobileMAN first phase | **R** | Pub | July 2004 | 7 August 2004 |
| **D9** | | MobileMAN intermediate evaluation report | **R** | Pub | September 2004 | 14 October 2004 |
| **D10** | | MobileMAN architecture, protocols, and services intermediate report | **R** | Pub | September 2004 | 14 October 2004 |

## Table 1c. DELIVERABLES TABLE

**Project Number:** IST-2001-38113

**Project Acronym:** MOBILEMAN

**Title:** Mobile Metropolitan Ad hoc Networks

| Del. No. | Revision | Title | Type[1] | Classification[2] | Due Date | Issue Date |
|---|---|---|---|---|---|---|
| **D11** | | MobileMAN functionalities – Enhanced Set | **S** | Pub | 31 October 2004 | 16 November 2004 |
| **D12** | | MobileMAN Wireless Network Interface | **O (**)** | Pub | 31 January 2005 | 23 February 2005 |
| **D13** | | MobileMAN domain modelling | **R** | Pub | 30 June 2005 (*) | 10 June 2005 |
| **D14** | | MobileMAN functionalities – final set | **S** | Pub | 31 August 2005 (*) | 1 September 2005 |
| **D15** | | MobileMAN Presentation | **W** | Pub | 31 July 2005 (*) | 29 July 2005 |

*(*) new schedule approved by the Project Officer after the three-month extension of the project length*

*(**) prototype of a complex electronic system composed of 5 parts (modem, voltage adaptor, DSP board, host PC, power supply). The system is an experimental and demonstration bench for research and verification of novel wireless communications, like the enhanced 802.11 PHY (optimized MAC) as specified in the MobileMAN project.*

## Table 1d. DELIVERABLES TABLE

**Project Number:** IST-2001-38113

**Project Acronym:** MOBILEMAN

**Title:** Mobile Metropolitan Ad hoc Networks

| Del. No. | Revision | Title | Type[1] | Classification[2] | Due Date | Issue Date |
|---|---|---|---|---|---|---|
| **D16** | | MobileMAN technical evaluation | Report | Pub. | 31 October 2005 (*) | 18 November 2005 |
| **D17** | | Socio-economic evaluation | Report | Pub. | 31 October 2005 (*) | 31 October 2005 |
| **D18** | | Economic value of self-organisation paradigm and market access | Report | Pub. | 31 October 2005 (*) | 31 October 2005 |
| **D19** | | Exploitation Plan | Report | Int. | 30 November 2005 (*) | 11 January, 2006 |
| **D20** | | Project final Report | Report | Pub. | 31 December 2005 (*) | -- |

*(*) new schedule approved by the Project Officer after the three-month extension of the project length*

## 5.2. References

Several different dissemination channels have been used to promote the project results this: (i) dissemination via web, newspapers, interviews, presentations; (ii) publishing and presenting results within the scientific community; (iii) organizing high-quality and focused scientific events for dissemination of project results; (iv) presenting/testing the MOBILEMAN solutions with/to users' communities; (v) dissemination of MOBILEMAN solutions to the industry and to the society; (vi) training of students.

These aspects have been discussed in depth in D19. A list of articles, conference presentations, etc. (updated to include the last month achievements) is reported in Section 8.

# 6. POTENTIAL IMPACT OF PROJECT RESULTS

In this section we summarize the potential impact of the project results. As area of ad hoc networking is of long-term nature, MobileMAN results have an impact mainly on the scientific community working on ad hoc networking. However, MobileMAN results show good potentialities from the innovation and economic standpoint. In the following we first summarize the potential impacts of the project results on advancing the knowledge on self-organize networks; then we discuss the contribution to European information society, and its socio-economic impact.

## *6.1. Scientific Impact*

Hereafter, we list the main contributions to the scientific literature.

- A pragmatic approach to develop, and implement innovative solutions for MANETs in realistic scenarios (small scale networks with legacy applications) based on implementation, integration and experimentation.

- We developed a methodology for designing multi-hop networks using cross-layer optimization still maintaining the layered organization of the network architecture.

- Validation of the cross-layer approach by a proof-of-concept prototype and simulation studies based on NS-2 extensions.

- An architecture and the related software to transparently interconnect ad hoc islands to the Internet

- The extensive experimental activities performed in the framework of the project contribute to remove a set of simplifying assumptions commonly used in simulative studies that caused a lack of credibility in most of the results so far obtained. In addition, experimental activities pointed out problems that have no been previously identified. It is worth remembering:
    - Experimental results about the behavior of 802.11 ad hoc networks.
    - Experimental results about the OLSR and AODV performance.
    - Experimental results of p2p platforms performance on multi-hop ad hoc network

- The algorithm designed and evaluated for the enhanced 802.11 card is very promising both from a scientific (and economic) standpoint.
    - It provides a formal basis to the activities of TG 802.11n that is working toward higher throughput for 802.11 networks. Indeed, AOB extended

with the credit mechanism provides an optimized and efficient solution to the multiple transmissions approach currently under study in TGn.
- It provides an efficient solution to fix 802.11 unfairness in multi-hop scenarios

## 6.2. Impact on European information society

- MOBILEMAN stimulated the growth of a European research community in this field; this will help to create expertise and knowledge in the field to support the European industry. MobileMAN partners created a kernel for the European research in the field that stimulated with several initiatives the growth of an European community in this field. See Deliverable D19 for details.

- MOBILEMAN addressed research issues that in the ISTAG time-framework are scheduled for 2007, and beyond. Therefore, the results of MOBILEMAN represent a basis for the future EU R&D activities on Ambient Intelligence and Pervasive Communications.

- MOBILEMAN stimulated the participation for all in the knowledge-based society; this has been done by involving several categories in the MobileMAN social analyses and identifying the reasons that limit social inclusion. This also helps in reducing the barriers to access this novel technology.

- Training of students in a relevant ICT area (i.e., wireless and mobile communications and networking), which is fundamental for the evolution of the European (information) society.

- Support for civilian and environmental crises management. This is important considering Europe's increasing role providing aid during conflicts and natural disasters.

## 6.3. Socio-economic impact

The area of ad hoc networking is of long-term nature. However, our results show good potentialities from the innovation and economic standpoint. Specifically,

- The algorithm designed and evaluated for the enhanced 802.11 card is very promising from an economic standpoint, too. The widespread usage of the 802.11 technologies and its economic value in the wireless market open to our solution (which is compatible with existing standards) extremely interesting business.

- We have identified new applications that can leverage the ad hoc technology to provide valuable services to the user. The city cab scenario (i.e., the use of 802.11 ad hoc networks to replace the currently used taxi radio dispatch systems) is the most promising one. We have found that, in this scenario, an ad hoc networking system is viable both economically and technically.

- Accelerating reforms in the wireless market is essential for higher growth and employment and increased consumer benefits. MOBILEMAN investigated how to realize a *secondary wireless market* (with respect to the cellular market) based on the ad hoc paradigm. While for infrastructure-based networking, wireless operators are best placed to assume the role of kingmaker in the infrastructure-less approach this position is challenged, as new developments do not require involvement from major infrastructure players. This significantly reduces the cost-barriers for creating new services and open the telecommunication market by fostering competition in the local accesses to Internet.

- Mesh networks constitute a short-term direction to turn mobile ad hoc networks in a commodity by providing a flexible and "low cost" extension of wired infrastructure networks.

- The usage of VoIP on top of ad hoc networks has interesting industrial potentialities. Nokia showed the interest to launch a project on this topic.

# 7. FUTURE OUTLOOK

Several directions can be envisaged to exploit the project results for future research activities. To this end we can identify three main directions which correspond to different ways an ad hoc networks can be implemented, hybrid networks (mesh networks), pure multi-hop ad hoc networks, and opportunistic or delay tolerant networks. These three directions also correspond to three different time-scale for research activities (short-term for mesh, medium term for MANETs and long-term for opportunistic networks).

For (pure) mobile ad hoc networks, the project results point out the limitations of current technologies (e.g., routing protocols so far developed needs a careful re-tuning and enhancements to correctly operate on multi-hop networks), and clearly indicate that ad hoc networking technology is promising but it is quite far from being a stable technology for building 4G networks. Further (basic) research efforts are still needed to overcome current limitations of this technology and to establish ad hoc networks as a building block of future networks. Cross layering is one of the most promising techniques for improving the efficiency of mobile ad hoc networks. It is interesting to note that a similar direction is currently pursued in USA where DARPA lunched the *Control-Based Mobile Ad-Hoc Networking* (CBMANET) Program http://www.darpa.mil/ato/solicit/cbmanet/index.htm. From an application standpoint, we believe that would be useful to established collaborations with people working in the public safety (from disaster recovery to all public-security activities) as in this field pure ad hoc networks have big potentialities that have not yet been explored.

While further basic research activities are needed for pure multi-hop ad hoc networks, the ideas, methods and software modules developed in the project, coupled with the know-how about implementing, configuring and testing multi-hop ad hoc networks, constitute the bases for Mesh Networks implementation. Indeed Mesh networks constitute the short-term direction to turn mobile ad hoc networks in a commodity by providing a flexible and "low cost" extension of wired infrastructure networks. In parallel with mesh networks deployment, we believe that MobileMAN results constitute a basis for new research activities aimed to construct mesh networks with Quality of Service (QoS) support.

Opportunistic networking is the long-term direction for exploitation of ad the project results. In such scenario, each device forwards data in an opportunistic way, i.e., by exploiting opportunistically any possible contact with other devices, thus making this paradigm very interesting for future pervasive computing and communications systems which will be be heterogeneous not only in the network technologies, but also in the user-QoS needs. The user will be able to seamlessly switch between different networking technologies, and will dynamically choose the one that better suits her needs. This scenario opens very challenging research directions that the project partners are currently exploring inside the newly lunched IST–FET projects under the proactive call "Situated and Autonomic Communications (SAC)". Specifically, MobileMAN partners are performing MobileMAN knowledge transfer to the following SAC projects:

- HAGGLE (http://www.haggleproject.org/),
- BIONETS (http://www.create-net.org/create-net/bio-nets/) and
- CASCADAS (http://netmob.unitn.it/cascadas/index.html).

# 8. PROJECT'S ASSESSMENT FICHE

(this part is still to be updated)

| Questions about project's outcomes | Number | Comments |
|---|---|---|
| **1. Scientific and technological achievements of the project (and why are they so ?)** | | |
| Question 1.1.<br><br>Breakthrough or "real" innovation | | The area of ad hoc networking is of long-term nature. Furthermore, the project is still in the phase in which solutions are developed and tested. However, preliminary results show good potentialities from the innovation and economic standpoint. Specifically,<br>a) the pragmatic approach of the project to develop, and implement innovative solutions for MANETs in realistic scenarios (small scale networks with legacy applications) is working towards lowering the barriers for ad hoc networking; we believe that this has to become a prime objective of MANET research to make it successful in everyday life.<br>b) We have defined and investigated scenarios in which the use of ad hoc networking solutions have a market value. The city cab scenario, i.e., the use of 802.11 ad hoc networks to replace the currently used taxi radio dispatch systems is viable both economically and technically.<br>c) The extensive experimental activities performed in the framework of the project contribute to remove a set of simplifying assumptions commonly used in simulative studies that caused a lack of credibility in most of the results so far obtained. In addition, experimental activities pointed out problems that have no been previously identified.<br>d) The implementation of a proof-of-concept prototype for a cross layer MANET architecture will provide a preliminary understanding of the benefits of this new approach in MANET design.<br>e) The algorithm designed and evaluated for the enhanced 802.11 card is very promising both from a scientific and economic standpoint.<br>• it provides a formal basis to the activities of TG 802.11n that is working toward higher throughput for 802.11 networks. Indeed, AOB extended with the credit mechanism provides an optimized and efficient solution to the multiple transmissions approach currently under study in TGn.<br>• It provides an efficient solution to fix 802.11 unfairness in multi-hop scenarios<br>• The widespread usage of the 802.11 technology, and its economic value in the wireless market, open to our solution (which is compatible with existing standards) extremely interesting opportunities for creating business opportunities. However, it must be pointed out that the development of the new card implementing the enhanced algorithm is still ongoing and hence, economic exploitation of this output of the project will be better evaluated after field tests of the new card. |

| | | |
|---|---|---|
| | | f) The usage of VoIP on top of Ad Hoc networks has interesting potentialities. After a MobileMAN presentation for Nokia Networks representatives, Nokia shows the interest to launch a project on this topic.<br>g) We have identified new applications that can leverage the ad hoc technology to provide valuable services to the user. The city cab scenario (i.e., the use of 802.11 ad hoc networks to replace the currently used taxi radio dispatch systems) is the most promising one. We have found that in this scenario, an ad hoc networking system is viable both economically and technically.<br>h) Mesh networks constitute a short-term direction to turn mobile ad hoc networks in a commodity by providing a flexible and "low cost" extension of wired infrastructure networks. |
| **2. Impact on Science and Technology: Scientific Publications in scientific magazines** | | |
| Question 2.1.<br><br>Scientific or technical publications on reviewed journals and conferences | 15 | Title and journals/conference and partners involved<br><br>1) R. Bruno, M. Conti, E. Gregori, "Mesh Networks: Commodity Multi-hop Ad Hoc Networks", *IEEE Communications Magazine*, March 2005, pp.123-131. (partner(s): CNR)<br>2) A. Anastasi , E. Borgia, M. Conti, E. Gregori, A. Passarella, "Understanding the Real Behavior of Mote and 802.11 Ad Hoc Networks: An Experimental Approach", *Pervasive and Mobile Computing* Journal, Vol 1, N. 2, June 2005. (partner(s): CNR)<br>3) M. Conti, E. Gregori, and G. Maselli, "Reliable and Efficient Forwarding in Ad Hoc Networks", *Ad Hoc Networks* Journal, (to appear). (partner(s): CNR)<br>4) M. Conti, G. Maselli, G. Turi, "A flexible cross-layer interface for ad hoc networks: Architectural and Implementation issues", *Ad Hoc & Sensor Wireless Networks: An International Journal* (Old City Publishing), (to appear). (partner(s): CNR)<br>5) M. Conti, E. Gregori, G. Turi, "A Cross Layer Optimization of Gnutella for Mobile Ad hoc Networks", Proc. ACM MobiHoc Symposium, Urbana-Champain, May 2005, pp.343-354. (partner(s): CNR)<br>6) E. Huang, W. Hu, J. Crowcroft, I. Wassell, "Towards Commercial MobileAd Hoc Network Applications: A radio Dispatch System" Proc. ACM MobiHoc Symposium, Urbana-Champain, May 2005, pp. 355-365. (partner(s): Cambridge)<br>7) G. Anastasi, E. Ancillotti, M. Conti, and A. Passarella, "TPA: A Transport Protocol for Ad hoc Networks", Proc. 10th IEEE Symposium on Computers and Communications, June 2005. (partner(s): CNR)<br>8) M. Conti, G. Maselli, and G. Turi, "Design and evaluation of a flexible cross-layer interface for |

| | | |
|---|---|---|
| | | ad hoc networks", Proceedings Fourth Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net 2005), June 2005 (21-24) Ile de Porquerolles (France). (partner(s): CNR)<br>9) Ralf Bernasconi, Raffaele Bruno, Ivan Defilippis, Silvia Giordano, and Alessandro Puiatti, "Experiments with an enhanced MAC architecture for multi-hop wireless networks", Proc. 1st IEEE ICPS Workshop on Multi-hop Ad hoc Networks: from theory to reality (REALMAN 2005), July 14, 2005, Santorini, Greece (partner(s): CNR and SUPSI)<br>10) Franca Delmastro and Andrea Passarella, "An Experimental Study of P2P Group-Communication Applications in Real-World MANETs", Proc. 1st IEEE ICPS Workshop on Multi-hop Ad hoc Networks: from theory to reality (REALMAN 2005), July 14, 2005, Santorini, Greece (partner(s): CNR and Cambridge)<br>11) E. Borgia, M. Conti, F. Delmastro, E. Gregori, "Experimental comparison of routing and middleware solutions for mobile ad hoc networks: legacy vs cross-layer approach", ACM SIGCOMM Workshop on Experimental Approaches to Wireless Network Design and Analysis (E-WIND) August 22, 2005 - Philadelphia, PA. (partner(s): CNR)<br>12) M. Conti, E. Gregori, G. Maselli "Improving the performability of data transfer in mobile ad hoc networks", Proc. Second IEEE International Conference on Sensor and Ad Hoc Communications and Networks (SECON), Santa Clara, CA, September 2005. (partner(s): CNR)<br>13) Raffaele Bruno, Claude Chaudet, M. Conti, E. Gregori, "A Novel Fair Medium Access Control for 802.11-based Multi-Hop Ad hoc Networks, Proc. 14th IEEE Workshop on Local and Metropolitan Area Networks, Chania, Greece, September, 2005. (partner(s): CNR)<br>14) Altman, Eitan; Kherani, Arzad; Michiardi, Pietro; Molva, Refik, "Non cooperative forwarding in ad hoc networks", Proc. IFIP Networking 2005 (partner(s): Eurecom)<br>15) Altman, Eitan; Borkar, Vivek; Kherani, Arzad; Michiardi, Pietro; Molva, Refik "Some game-theoretic problems in wireless ad hoc networks" Proc. EURO-NGI 2005. (partner(s): Eurecom) |
| Question 2.2.<br><br>Scientific or technical publications on non-reviewed journals and conferences | 0 | Title and journals/conference and partners involved |
| Question 2.3. | | |

| | | |
|---|---|---|
| Invited papers published in scientific or technical journal or conference. | 4 | Title and journals/conference and partners involved<br><br>1) M. Conti, F. Delmastro, T. Turi, "Peer-to-peer Computing in Mobile Ad Hoc Networks", in *Mobile Middleware,* Antonio Corradi and Paolo Bellavista (Editors), CRC press (To appear) . (partner(s): CNR)<br>2) Raffaele Bruno, Claude Chaudet, Marco Conti and Enrico Gregori, "Fair MAC Protocols for 802:11-based Multi-Hop Ad hoc Networks: Challenges and Solutions" in *Performance Analysis of Mobile Ad Hoc Networks*, Chita Das, Yi Pan Chansu Yu (Editors) Nova Science Publishers Inc. (to appear) . (partner(s): CNR)<br>3) M. Conti, Peer-to-peer Computing in Mobile Ad Hoc Networks, in *Mobile Middleware* Antonio Corradi and Paolo Bellavista (Editors), CRC Press (to appear) . (partner(s): CNR)<br>4) P. Michiardi, R. Molva, "Ad hoc network security"Chapter in Book: Handbook of information security IEEE Press, Wiley & Sons (to appear) . (partner(s): Eurecom) |
| **3. Impact on Innovation and Micro-economy** | | |
| **A - Patents** | | |
| Question 3.1.<br><br>Patents filed and pending | 0 | When and in which country(ies):<br><br>Brief explanation of the field covered by the patent*: |
| Question 3.2.<br><br>Patents awarded | 0 | When and in which country(ies):<br><br>Brief explanation of the field covered by the patent* (if different from above): |
| Question 3.3.<br><br>Patents sold | 0 | When and in which country(ies):<br><br>Brief explanation of the field covered by the patent* (if different from above): |

| **Programme Area: IST FET**<br>**Project Acronym: MOBILEMAN** | **Date of filling: 21/01/2006** |
|---|---|

| | | |
|---|---|---|
| **Questions about project's outcomes** | **Number** | **Comments or suggestions for further investigation** |
| **B - Start-ups** | | |
| Question 3.4.<br><br>Creation of start-up | No | If YES, details:<br>- date of creation:<br>- company name:<br>- location:<br>- headcount:<br>- turnover:<br>- profitable : yes / no |
| Question 3.5.<br><br>Creation of new department of research (ie: organisational change) | Yes | Name of department:<br><br>A Joint laboratory has been created between IIT-CNR and the University of Pisa: *Pervasive Computing & Networking Lab*. (PerLab); http://www.perlab.it<br><br>Currently, the procedures for the creation of a research association "ANTARES: Association for NeTworking Advanced RESearch" between IIT-CNR and Univeristy of Pisa are ongoing. |
| **C – Technology transfer of project's results** | | |
| Question 3.6.<br><br>Collaboration/ partnership with a company ? | Yes | Which company : BTexact Technologies, Nokia, Siemens, ST Microelectronics<br>What kind of collaboration?<br>Project Industrial Advisory Board<br><br>Which company : Intel Research, Thomson, Telecom Italia |

| | | |
|---|---|---|
| | | What kind of collaboration?<br>Project activities |
| **4. Other effects** | | |
| **A - Participation to Conferences/Symposium** | | |
| Question 4.1.<br><br>Active participation[4] to Conferences in **EU**<br>(specify if one partner or "collaborative" between partners) | 6 | Names/ Dates/ Country:<br><br>- The Second Conference on Wireless On-demand Network Systems and Services (WONS 2005), Saint Moritz (Switzerland) January 19-21, 2005 (partner(s): CNR, SUPSI).<br>- The 6th IEEE Symposium on a World of Wireless Mobile and Multimedia Networks (WoWMoM 2005), Taormina, Italy June 2005. (partner(s): CNR).<br>- The 1st IEEE ICPS Workshop on Multi-hop Ad hoc Networks: from theory to reality (REALMAN 2005), July 14, 2005, Santorini, Greece (partner(s): CNR, Cambridge).<br>- 1st Conference on Wireless Internet (WICON 2005), Budapest, Hungary, 10-15 July 2005 (partner(s): Cambridge).<br>- 1st IEEE WoWMoM Workshop on Autonomic Communications and Computing (ACC 2005), (partner(s): CNR, SUPSI).<br>- 1st IEEE WoWMoM Workshop on Trust, Security and Privacy for Ubiquitous Computing (TSPUC2005) (partner(s): Eurecom). |
| Question 4.2.<br><br>Active participation to Conferences outside the **EU**<br>(specify if one partner or "collaborative" between partners) | 3 | Names/ Dates/ Country:<br><br>- Third IEEE Conference on Pervasive Computing and Communications (PerCom) 2005, Kauai, Hawaii, March 8-12, 2005. (partner(s): CNR).<br>- Special track on *Energy Management in Mobile and Pervasive Computing Systems* at the 38th Annual Hawaii International Conference on System Sciences, 2005. (partner(s): CNR). |

[4] 'Active Participation' in the means of being an invited speaker or organising a workshop / session / stand / exhibition directly related to the project (apart from events presented in section 2).

| | | |
|---|---|---|
| | | - Fourth Workshop on Hot Topics in Networks (HotNets-IV), November 14-15, 2005 College Park, MD USA (partner(s): Cambridge). |
| **B – Training effect** | | |
| Question 4.3.<br><br>Number of PhD students hired for project's completion | 7 | In what field :<br><br>Computer Science<br>Computer Engineering<br>Telecommunications |
| **Questions about project's outcomes** | **Number** | **Comments or suggestions for further investigation** |
| **C - Public Visibility** | | |
| Question 4.4.<br><br>Media appearances and general publications (articles, press releases, etc.) | 10 | References*:<br>**Almanacco della Scienza** Rivista on line del Consiglio Nazionale delle Ricerche<br>8 Giugno, 2005<br>http://150.146.47.106/rivistaonline/documenti/storiadicopertina/06_8_2005.htm<br>**La Nazione** (national newspaper)– Firenze 23 May, 2005 (page 16) "Ecco il cellulare gratuito. Crea la rete da solo e può avere mille usi" - not available on line<br><br>Il **Tempo** (national newspaper)– Roma 9 August 2005 "Mobileman» la rete senza fili e infrastrutture"<br><br>http://www.iltempo.it/approfondimenti/index.aspx?id=746320&editionId=5&SectionId=4 |

| | | |
|---|---|---|
| | | **La Repubblica** – Affari e Finanza 7 November 2005<br><br>http://www.repubblica.it/2005/j/sezioni/scienza_e_tecnologia/wifi/senzaintern/senzaintern.html<br><br>- The web site of the Italian public TV:<br><br>• http://www.rai.it/accessibile/news/articolonews/0,9217,107754,00.html<br><br>• http://www.raifiction.rai.it/news/articolonews/0,9217,107754,00.html<br><br>– Adnkronos news agency web site<br><br>http://www.adnkronos.com/Speciali/Scienza/NotizieManuali/01_2504.html<br>– Portals devoted to ICT technologies<br><br>• http://www.i-dome.com/flash-news/pagina.phtml?_id_articolo=8559<br>• http://www.heos.it/tecno_05/tecno_12.htm<br>• http://www.weekit.it/index2.php?option=com_content&do_pdf=1&id=36334 |
| Question 4.5.<br><br>Web-pages created or other web-site links related to the project | 8 | References*:<br><br>http://cnd.iit.cnr.it/mobileMAN/<br><br>http://mobileman.projects.supsi.ch<br><br>http://keskus.hut.fi/tutkimus/MobileMan/<br><br>http://www.cl.cam.ac.uk/Research/SRG/netos/sla/mobileman/mobileman.pdf |

| | | |
|---|---|---|
| | | http://www.ti.edu.ch/servizi/ricerca/ricerca_attualita/progettomese/2/ricerca_progetto.htm<br><br>http://www.aramis-research.ch/d/17406.html<br><br>http://pi.ijs.si/ProjectIntelligence.Exe?Cm=Project&Project=MOBILEMAN |
| Question 4.6.<br><br>Video produced or other dissemination material | 0 | References*: |
| Question 4.7.<br><br>Key pictures of results | 0 | References*: |
| **D - Spill-over effects** | | |
| Question 4.8.<br><br>Any spill-over to national programs | Yes | If YES, which national programme(s):<br><br>CNR: Virtual Immersive Communications (VICOM) is a three years Italian project (Nov. 2002 – Nov. 2005) funded by the Italian Ministry for Research (MIUR) in the FIRB framework<br><br>Italian Ministry for Research - three-year Italian national plan for research (2005-2008).<br><br>Eurecom : CNRS / ACI SPlaSH: Sécurisation des ProtocoLes dans les réseAux mobileS ad Hoc.<br><br>HUT : national projects:<br>*Project AHRAS (http://www.netlab.hut.fi/tutkimus/ahras/)*<br>concentrates on the routing and other traffic related issues in wireless ad hoc networks. The project started in 2001 and it is funded by the Finnish Defence Forces Technical Research Centre.<br><br>*Project NAPS (Networking and Architecture for Proactive Systems)* is a 3 year project (2003-2005) funded by the Academy of Finland. It is part of the research programme on Proactive Computing |

| | | |
|---|---|---|
| | | (PROACT). http://www.netlab.hut.fi/tutkimus/naps/ |
| Question 4.9.<br><br>Any spill-over to another part of EU IST Programme | Yes | If YES, which IST programme(s):<br><br>**WIDENS**: WIreless DEployable Network System, Proposal acronym,<br>The project is supported by the European Commission under the IST Framework Programme 6. http://www.widens.org/<br><br>**E-NeXT:** Network of Excellence Emerging Network Technologies http://www.ist-e-next.net/<br>E-NEXT is an FP6 Network of Excellence<br><br>**HAGGLE:** IST – FET proactive "Situated and Autonomic Communications" project<br>http://www.haggleproject.org<br><br>**BIONETS:** IST – FET proactive "Situated and Autonomic Communications" project http://www.create-net.org/create-net/bio-nets/ |
| Question 4.10.<br><br>Are other team(s) involved in the same type of research as the one in your project ? | Yes | If YES, which organisation(s):<br><br>**EQUATOR.** This is a six-year Interdisciplinary Research Collaboration (IRC) supported by The Engineering and Physical Sciences Research Council (EPSRC) of the UK Government.<br>http://www.interaction.rca.ac.uk/equator/<br><br>**MMAPPS:** *Market Management of Peer to Peer Services*. The MMAPPS project started on March 1st, 2002 with funding from the EU Fifth RTD Framework Programme. http://www.mmapps.org/<br><br>**ROMANTIK:** ResOurce Managment and AdvaNced Transceiver algorIthms for multihop networKs (IST-2001-32549) funded from the EU Fifth RTD Framework Programme. http://www.ist-romantik.org/<br><br>**UCAN**: Ultra-wideband Concepts for Ad-hoc Networks (**IST-2001-32710**), funded from the EU Fifth |

| | | |
|---|---|---|
| | | RTD Framework Programme http://www.ucan.biz/<br><br>**BROADWAY:** The way to broadband access at 60GHz (**IST-2001-32686**) funded from the EU Fifth RTD Framework Programme.<br>http://www.ist-broadway.org/<br><br>**6HOP**: Protocols for Heterogeneous Multi-Hop Wireless IPv6 Networks (**IST-2001-37385**) funded from the EU Fifth RTD Framework Programme.<br>http://www.cwc.oulu.fi/projects/6hop/<br><br>**WIDENS:** WIreless DEployable Network System, Proposal acronym () The project is supported by the European Commission under the IST Framework Programme 6. http://www.widens.org/ |