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An Overview of Mobile Ad Hoc Networks: Applications and Challenges

In the past few years, we have seen a rapid expansion in the field of mobile computing due to the proliferation of inexpensive, widely available wireless devices. However, current devices, applications and protocols are solely focused on cellular or wireless local area networks (WLANs), not taking into account the great potential offered by mobile ad hoc networking. A mobile ad hoc network is an autonomous collection of mobile devices (laptops, smart phones, sensors, etc.) that communicate with each other over wireless links and cooperate in a distributed manner in order to provide the necessary network functionality in the absence of a fixed infrastructure. This type of network, operating as a stand-alone network or with one or multiple points of attachment to cellular networks or the Internet, paves the way for numerous new and exciting applications. Application scenarios include, but are not limited to: emergency and rescue operations, conference or campus settings, car networks, personal networking, etc.

This paper provides insight into the potential applications of ad hoc networks and discusses the technological challenges that protocol designers and network developers are faced with. These challenges include routing, service and resource discovery, Internet connectivity, billing and security.

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Introduction

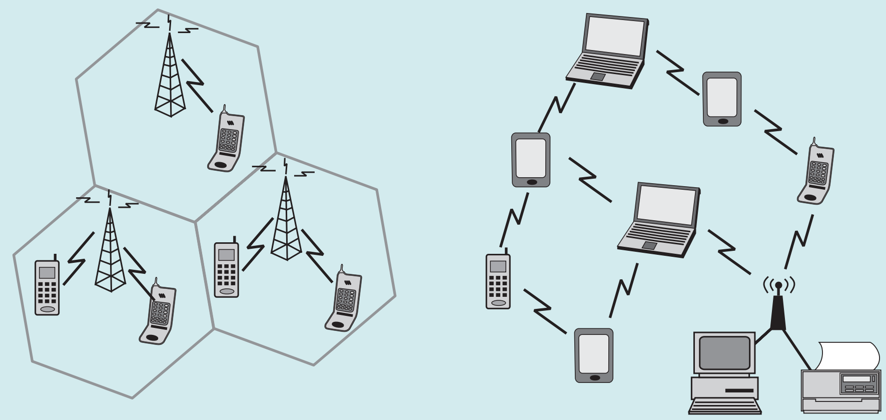
The field of wireless and mobile communications has experienced an unprecedented growth during the past decade. Current second-generation (2G) cellular systems have reached a high penetration rate, enabling worldwide mobile connectivity. Mobile users can use their cellular phone to check their email and browse the Internet. Recently, an increasing number of wireless local area network (LAN) hot spots is emerging, allowing travellers with portable computers to surf the Internet from airports, railways, hotels and other public locations. Broadband Internet access is driving wireless LAN solutions in the home for sharing access between computers. In the meantime, 2G cellular networks are evolving to 3G, offering higher data rates, infotainment and location-based or personalised services.

However, all these networks are conventional wireless networks, conventional in the sense that as prerequisites, a fixed network infrastructure with centralised administration is required for their operation, potentially consuming a lot of time and money for set-up and maintenance. Furthermore, an increasing number of devices such as laptops, personal digital assistants (PDAs), pocket PCs, tablet PCs, smart phones, MP3 players, digital cameras, etc. are provided with short-range wireless interfaces. In addition, these devices are getting smaller, cheaper, more user friendly and more powerful. This evolution is driving a new alternative way for mobile communication, in which mobile devices form a self-creating, self-organising and self-administering wireless network, called a *mobile ad hoc network*. This paper discusses the characteristics, possible applications and network layer challenges of this promising type of network.

History and Definition of Mobile Ad Hoc Networks

Opposed to infrastructured wireless networks, where each user directly communicates with an access point or base station, a mobile ad hoc network, or *MANET*, does not rely on a fixed infrastructure for its operation (Figure 1)[1]. The network is an autonomous transitory association of mobile nodes that communicate with each other over wireless links. Nodes that lie within each other's send range can communicate directly and are responsible for dynamically discovering each other. In order to enable communication between nodes that are not directly within each other's send range, intermediate nodes act as routers that relay

Figure 1 Cellular networks versus mobile ad hoc networks



(a) Cellular network   (b) Mobile ad hoc network

packets generated by other nodes to their destination. These nodes are often energy-constrained—that is, battery-powered—devices with a great diversity in their capabilities. Furthermore, devices are free to join or leave the network and they may move randomly, possibly resulting in rapid and unpredictable topology changes. In this energy-constrained, dynamic, distributed multi-hop environment, nodes need to organise themselves dynamically in order to provide the necessary network functionality in the absence of fixed infrastructure or central administration.

The specific characteristics and complexities, which are summarised in Table 1, impose many design challenges to the network protocols. In addition, these networks are faced with the traditional problems inherent to wireless communications such as lower reliability than wired media, limited physical security, time-varying channels, interference, etc.

Despite the many design constraints, mobile ad hoc networks offer numerous advantages. First of all, this type of network is highly suited for use in situations where a fixed infrastructure is not available, not trusted, too expensive or unreliable. Because of their self-creating, self-organising and self-administering capabilities, ad hoc networks can be rapidly deployed with minimum user intervention. There is no need for detailed planning of base station installation or wiring. Also, ad hoc networks do not need to operate in a stand-alone fashion, but can be attached to the Internet, thereby integrating many different devices and making their services available to other users. Furthermore, capacity, range and energy arguments promote their use in tandem with existing cellular infrastructures as they can extend coverage and interconnectivity. As a consequence, mobile ad hoc networks are expected to become an important part of the future 4G architecture, which aims to provide pervasive computer environments that support users in accomplishing their tasks, accessing information and communicating anytime, anywhere and from any device. Table 2 provides an overview of present and future MANET applications, partially based on Reference 2.

Table 1 Characteristics and complexities of mobile ad hoc networks

Autonomous and infrastructureless
Multi-hop routing
Dynamic network topology
Device heterogeneity
Energy constrained operation
Bandwidth constrained variable capacity links
Limited physical security
Network scalability
Self-creation, self-organization and self-administration

Table 2 Mobile ad hoc network applications

Application	Possible scenarios/services
Tactical networks	• Military communication and operations • Automated battlefields
Emergency services	• Search and rescue operations • Disaster recovery • Replacement of fixed infrastructure in case of environmental disasters • Policing and fire fighting • Supporting doctors and nurses in hospitals
Commercial and civilian environments	• E-commerce: electronic payments anytime and anywhere • Business: dynamic database access, mobile offices • Vehicular services: road or accident guidance, transmission of road and weather conditions, taxi cab network, inter-vehicle networks • Sports stadiums, trade fairs, shopping malls • Networks of visitors at airports
Home and enterprise networking	• Home/office wireless networking • Conferences, meeting rooms • Personal area networks (PAN), Personal networks (PN) • Networks at construction sites
Education	• Universities and campus settings • Virtual classrooms • Ad hoc communications during meetings or lectures
Entertainment	• Multi-user games • Wireless P2P networking • Outdoor Internet access • Robotic pets • Theme parks
Sensor networks	• Home applications: smart sensors and actuators embedded in consumer electronics • Body area networks (BAN) • Data tracking of environmental conditions, animal movements, chemical/biological detection
Context aware services	• Follow-on services: call-forwarding, mobile workspace • Information services: location specific services, time dependent services • Infotainment: touristic information
Coverage extension	• Extending cellular network access • Linking up with the Internet, intranets, etc.

The concept of mobile ad hoc networking is not a new one and its origins can be traced back to the DARPA Packet Radio Network project in 1972[3]. Then, the advantages such as flexibility, mobility, resilience and independence of fixed infrastructure, elicited immediate interest among military, police and rescue agencies in the use of such networks under disorganised or hostile environments. For a long time, ad hoc network research stayed in the realm of the military, and only in the middle of 1990, with the advent of commercial radio technologies, did the wireless research community become aware of the great potential and advantages of mobile ad hoc networks outside the military domain, witnessed by the creation of the Mobile Ad Hoc Networking working group within the IETF[4]. Currently, mobile ad hoc network research is a very vibrant and active field and the efforts of the research community, together with current and future MANET enabling radio technologies, which are summarised in Table 3, will certainly pave the way for commercially viable MANETs and their new and exciting applications, with some of these commercially oriented solutions already starting to appear (for example MeshNetworks† and SPANworks*).

† http://www.meshnetworks.com
* http://www.spanworks.com

Technological Challenges

As already stated, the specific characteristics of MANETs impose many challenges to network protocol designs on all layers of the protocol stack[5]. The physical layer must deal with rapid changes in link characteristics. The media access control (MAC) layer needs to allow fair channel access, minimise packet collisions and deal with hidden and exposed terminals. At the network layer, nodes need to cooperate to calculate paths. The transport layer must be capable of handling packet loss and delay characteristics that are very different from wired networks. Applications should be able to handle possible disconnections and reconnections. Furthermore, all network protocol developments need to integrate smoothly with traditional networks and take into account possible security problems. In the following sections, technological challenges and possible solutions related to unicast routing, resource and service discovery, addressing and Internet connectivity, security and node cooperation are covered in more detail.

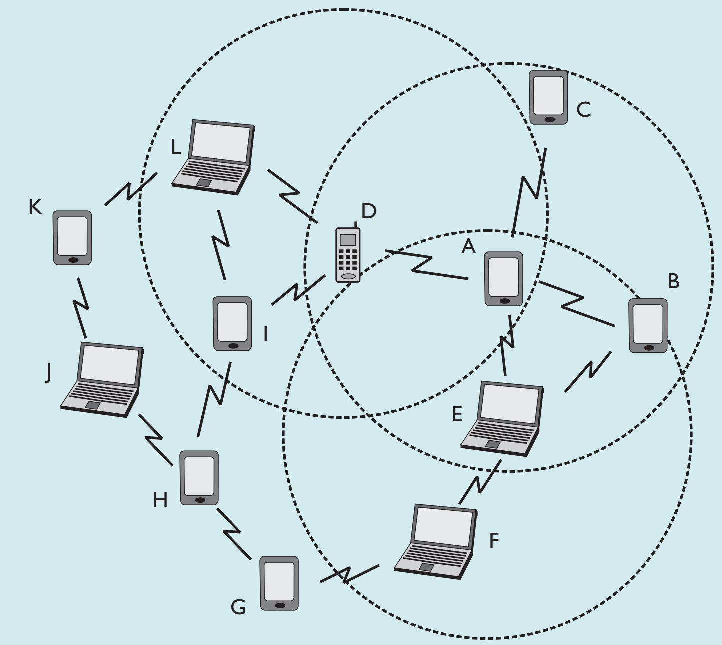
Routing

As mobile ad hoc networks are characterised by a multi-hop network topology that can change frequently due to mobility, efficient routing protocols are needed to establish communication paths between nodes, without causing excessive control traffic overhead or computational burden on the power constrained devices[6]. A large number of solutions have already been proposed, some of them being subject to standardisation within the IETF. A number of proposed solutions attempts to have an up-to-date route to all other nodes at all times. To this end, these protocols exchange routing control information periodically and on topological changes. These protocols, which are called *proactive* routing protocols, are typically modified versions of traditional link state or distance vector routing protocols encountered in wired networks, adapted to the specific requirements of the dynamic mobile ad hoc network environment. Most of the time, it is not necessary to have an up-to-date route to all other nodes. Therefore, *reactive* routing protocols only set up routes to nodes they communicate with and these routes are kept alive as long as they are needed. Combinations of proactive and reactive protocols, where nearby routes (for example, maximum two hops) are kept up-to-date proactively, while far-away routes are set up reactively, are also possible and fall in the category of *hybrid* routing protocols. A completely different approach is taken by the *location-based* routing protocols, where packet forwarding is based on the location of a node's communication partner. Location information services provide nodes with the location of the others, so packets can be forwarded in the

Table 3 Mobile ad hoc network enabling technologies

Technology	Theoretical bit rate	Frequency	Range	Power consumption
IEEE 802.11b	1, 2, 5.5 and 11 Mbit/s	2.4 GHz	25–100 m (indoor) 100–500 m (outdoor)	~30 mW
IEEE 802.11g	Up to 54 Mbit/s	2.4 GHz	25–50 m (indoor)	~79 mW
IEEE 802.11a	6, 9, 12, 24, 36, 49 and 54 Mbit/s	5 GHz	10–40 m (indoor)	40 mW, 250 mW or 1 W
Bluetooth (IEEE 802.15.1)	1 Mbit/s (v1.1)	2.4 GHz	10 m (up to 100 m)	1 mW (up to 100 mW)
UWB (IEEE 802.15.3)	110 – 480 Mbit/s	Mostly 3 – 10 GHz	~10 m	100 mW, 250 mW
IEEE 802.15.4 (for example, Zigbee)	20, 40 or 250 kbit/s	868 MHz, 915 MHz or 2.4 GHz	10–100 m	1 mW
HiperLAN2	Up to 54 Mbit/s	5 GHz	30–150 m	200 mW or 1 W
IrDA	Up to 4 Mbit/s	Infrared (850 nm)	~10 m (line of sight)	Distance based
HomeRF	1 Mbit/s (v1.0) 10 Mbit/s (v2.0)	2.4 GHz	~50 m	100 mW
IEEE 802.16 IEEE 802.16a IEEE 802.16e (Broadband Wireless)	32 – 134 Mbit/s up to 75 Mbit/s up to 15 Mbit/s	10–66 GHz < 11 GHz < 6 GHz	2–5 km 7–10 km (max 50 km) 2–5 km	Complex power control

Figure 2 Overview of existing unicast routing techniques



Routing Type	Routing knowledge of node A when it communicates with nodes B, F and J	Protocols
Proactive	A has route to B, C, D, E, F, G, H, I, J, K and L (all nodes)	OLSR, TBRPF, WRP
Reactive	A has only route to B, F and J	AODV, DSR
Hybrid	A has route to B, C, D, E, F, I and L proactively and route to J reactively	ZRP
Location Based	A knows at least the location of its neighbours B, C, D and E and the location of F and J	DREAM, LAR

direction of the destination. Figure 2 provides an overview in terms of routing table content of the proposed solutions. Reference 7 provides an extensive overview of routing protocol research.

Simulation studies have revealed that the performance of routing protocols in terms of throughput, packet loss, delay and control overhead strongly depends on the network conditions such as traffic load, mobility, density and the number of nodes[8]. Ongoing research at Ghent University therefore investigates the possibility of developing protocols capable of dynamically adapting to the network[9].

Service and resource discovery

MANET nodes may have little or no knowledge at all about the capabilities of, or services offered by, each other. Therefore, service and resource discovery mechanisms, which allow devices to automatically locate network services and to advertise their own capabilities to the rest of the network, are an important aspect of self-configurable networks[10]. Possible services or resources include storage, access to databases or files, printer, computing power, Internet access, etc.

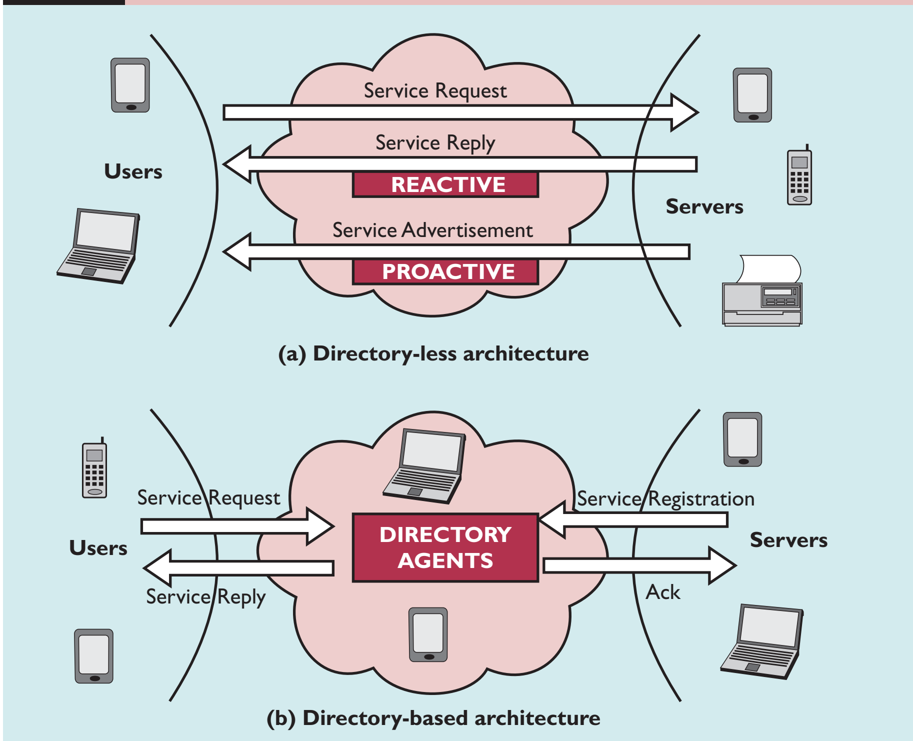
Directory-less service and resource discovery mechanisms, in which nodes reactively request services when needed and/or nodes proactively announce their services to others, seem an attractive approach for infrastructureless networks (Figure 3(a)). The alternative scheme is *directory-based* and involves directory agents where services are registered and service requests are handled (Figure 3(b)). This implies that this functionality should be statically or dynamically assigned to a subset of the nodes and kept up-to-date. Existing directory-based service and resource discovery mechanisms such as UPnP† or Salutation* are unable to deal with the dynamics in ad hoc networks. Currently, no mature solution exists, but it is clear that the design of these protocols should be done in close cooperation with the routing protocols and should include context-awareness (location, neighbourhood, user profile, etc.) to improve performance. Also, when ad hoc networks are connected to fixed infrastructure (for example, Internet, cellular network, etc.), protocols and methods are needed to inject the available external services offered by service and content providers into the ad hoc network.

Addressing and Internet connectivity

In order to enable communication between nodes within the ad hoc network, each node needs an address. In stand-alone ad hoc networks, the use of IP addresses is not per se obligatory, as unique MAC addresses could be used to address nodes. However, all current applications are based on TCP/IP or UDP/IP. In addition, as future mobile ad hoc networks will interact with IP-based

† http://www.upnp.org/
* http://www.salutation.org/

Figure 3 Logical overview of service and resource discovery architectures



networks and will run applications that use existing Internet protocols such as transmission control protocol (TCP) and user datagram protocol (UDP), the use of IP addresses is inevitable. Unfortunately, an internal address organisation with prefixes and ranges like in the fixed Internet is hard to maintain in mobile ad hoc networks due to node mobility and overhead reasons and other solutions for address assignment are thus needed.

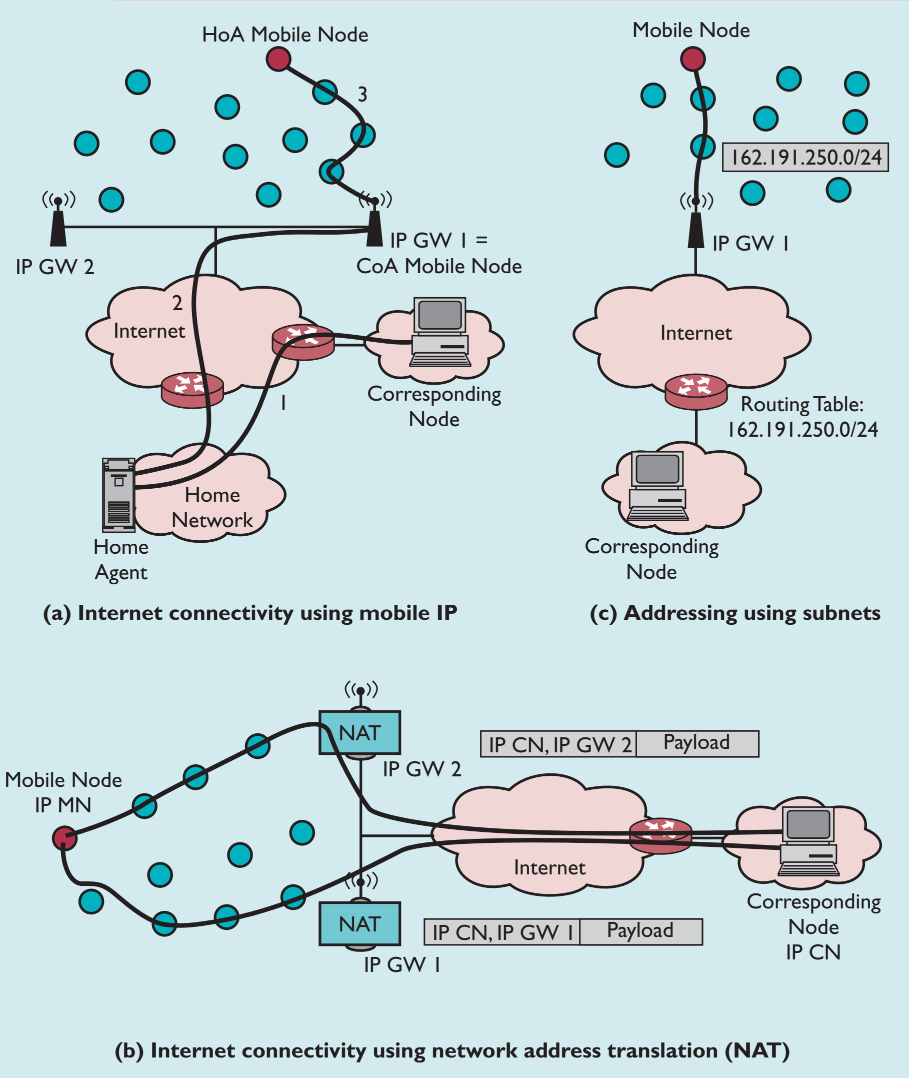
One solution is based on the assumption (and restriction) that all MANET nodes already have a static, globally unique and pre-assigned IPv4 or IPv6 address. This solves the whole issue of assigning addresses, but introduces new problems when interworking with fixed networks. Connections coming from and going to the fixed network can be handled using mobile IP (Figure 4(a))[11], where the pre-assigned IP address serves as the mobile node's home address (HoA). All traffic sent to this IP address will arrive at the node's home agent (HA) (step 1). When the node in the ad hoc network advertises to its home agent the IP address of the Internet gateway as its care-of-address (CoA), the home agent can tunnel all traffic to the ad hoc network (step 2), on which it is delivered to the mobile node using an ad hoc routing protocol (step 3). For outgoing connections, the mobile node has to route traffic to an Internet gateway, and for internal traffic an ad hoc routing protocol can be used. The main problem with this approach is that a MANET node needs an efficient way to figure out if a certain address is present in the MANET or if it is necessary to use an Internet gateway, without flooding the entire network.

Another solution is the assignment of random, internally unique addresses. This can be realised by having each node picking a more or less random address from a very large address space, followed by duplicate address detection (DAD) techniques in order to impose address uniqueness within the MANET. Strong DAD techniques will always detect duplicates, but are difficult to scale in large networks. Weak DAD approaches can tolerate duplicates as long as they do not interfere with each other; that is, if packets always arrive at the intended destination. If interconnection to the Internet is desirable, outgoing connections could be realised using network address translation (NAT), but incoming connections still remain a problem if random, not globally routable, addresses are used. Also, the use of NAT remains problematic when multiple Internet gateways are present. If a MANET node switches to another gateway, a new IP address is used and ongoing TCP connections will break (Figure 4(b)).

Another possible approach is the assignment of unique addresses that all lie within one subnet (comparable to the addresses assigned by a dynamic host configuration protocol (DHCP) server). When attached to the Internet, the ad hoc network can be seen as a separate routable subnet (Figure 4(c)). This simplifies the decision if a node is inside or outside the ad hoc network. However, no efficient solutions exist for choosing dynamically an appropriate, externally routable and unique network prefix (for example, special MANET prefixes assigned to Internet gateways), handling the merging or splitting of ad hoc networks, handling multiple points of attachment to the Internet, etc.

The above discussion makes clear that, although many solutions are being investigated[12], no common adopted solution for addressing and Internet connectivity is available yet. New approaches using host identities, where the role of IP is limited to routing and not addressing, combined with dynamic name spaces, could offer a potential solution.

Figure 4 Possible approaches to Internet connectivity and addressing



(a) Internet connectivity using mobile IP

(c) Addressing using subnets

(b) Internet connectivity using network address translation (NAT)

Security and node cooperation

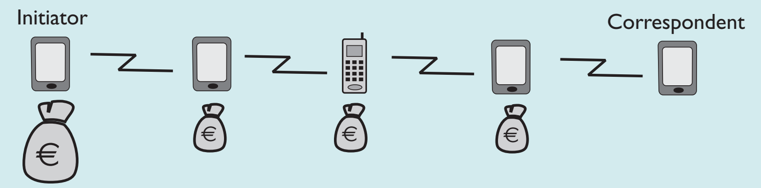
The wireless mobile ad hoc nature of MANETs brings new security challenges to the network design[13]. As the wireless medium is vulnerable to eavesdropping and ad hoc network functionality is established through node cooperation, mobile ad hoc networks are intrinsically exposed to numerous security attacks. During passive attacks, an attacker just listens to the channel in order to discover valuable information. This type of attack is usually impossible to detect, as it does not produce any new traffic in the network. On the other hand, during active attacks an attacker actively participates in disrupting normal operation of the network. This type of attack involves deletion, modification, replication, redirection and fabrication of protocol control packets or data packets. Securing ad hoc networks against malicious attacks is difficult to achieve. Preventive mechanisms include among others authentication of message sources, data integrity and protection of message sequencing, and are typically based on key-based cryptography. Incorporating cryptographic mechanisms is challenging, as there is no centralised key distribution centre or trusted certification authority. These preventative mechanisms need to be sustained by detection techniques that can discover attempts to penetrate or attack the network.

The previous problems were all related to malicious nodes that intentionally damage or compromise network functionality. However, selfish nodes, which use the network but do not cooperate to routing or packet forwarding for others in order not to spill battery life or network bandwidth, constitute an important problem as network functioning entirely relies on the cooperation between nodes and their contribution to basic network functions. To deal with these problems, the self-organising network concept must be based on an incentive for users to collaborate, thereby avoiding selfish behaviour. Existing solutions aim at detecting and isolating selfish nodes based on watchdog mechanisms, which identify misbehaving nodes, and reputation systems, which allow nodes to isolate selfish nodes. Another promising approach is the introduction of a billing system into the network based on economical models to enforce cooperation[14]. Using virtual currencies or micro-payments, nodes pay for using other nodes' forwarding capabilities or services and are remunerated for making theirs available (Figure 5).

This approach certainly has potential in scenarios in which part of the ad hoc network and services is deployed by companies or service providers (for example, location- or context-aware services, sports stadium, taxi cab network, etc.). Also, when ad hoc networks are interconnected to fixed infrastructures by gateway nodes, which are billed by a telecom operator (for example, UMTS, hot-spot access, etc.), billing mechanisms are needed to remunerate these nodes for making these services available. Questions such as who is billing, to whom and for what, need to be answered and will lead to complex business models.

We may conclude that in some ad hoc network scenarios, the network organisation can completely or partially rely on a trust relationship between participating nodes (for example, PANs). In many others, security mechanisms, mechanisms to enforce cooperation between nodes or billing methods are needed and will certainly be an important subject of future research.

Figure 5 **Enforcing cooperation by remunerating nodes for relaying packets**



Conclusions

The rapid evolution in the field of mobile computing is driving a new alternative way for mobile communication, in which mobile devices form a self-creating, self-organising and self-administering wireless network, called a *mobile ad hoc network*. Its intrinsic flexibility, lack of infrastructure, ease of deployment, auto-configuration, low cost and potential applications make it an essential part of future pervasive computing environments. As a consequence, the seamless integration of mobile ad hoc networks with other wireless networks and fixed infrastructures will be an essential part of the evolution towards future fourth-generation communication networks. From a technological point of view, the realisation of this vision still requires a large number of challenges to be solved related to devices, protocols, applications and services. The concise discussion in this paper shows that, despite the large efforts of the MANET research community and the rapid progress made during the last years, a lot of challenging technical issues remain unanswered. From an economical point of view, mobile ad hoc networks open up new business opportunities for telecom operators and service providers. To this end, appropriate business scenarios, applications and economical models need to be identified, together with technological advances, making a transition of ad hoc networks to the commercial world viable.

Acknowledgements

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Jeroen Hoebeke graduated in Computer Science at the University of Ghent in 2002. In August 2002, he joined the Broadband Communications Networks Group, where he is currently working as a research assistant of the Fund for Scientific Research Flanders. His Ph.D. research includes the development of adaptive routing protocol techniques for mobile ad hoc networks. His main research interests are in ad hoc networks and broadband wireless communications and currently involve routing, monitoring, resource discovery and mobility modelling of mobile ad hoc networks.

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Ingrid Moerman received the degree in Electro-technical Engineering and the Ph.D. degree from the Ghent University, Ghent, Belgium, in 1987 and 1992, respectively. Since 1987, she has been with the Interuniversity Micro-Electronics Centre (IMEC) at the Department of Information Technology (INTEC) of the Ghent University, where she conducted research in the field of optoelectronics. In 1997, she became a permanent member of the Research Staff at IMEC. Since 2000, she has been part-time professor at Ghent University. Since 2001, she has switched her research domain to broadband communication networks. She is currently involved in research and education on broadband mobile and wireless communication networks and on multimedia over IP. The main research topics related to mobile and wireless communication networks are: wireless access to vehicles (high bandwidth and driving speed), adaptive QoS routing in wireless ad hoc networks, body area networks, protocol boosting on wireless links, design of fixed access/metro part, traffic engineering and QoS support in the wireless access network. She is author or co-author of more than 300 publications in the field of optoelectronics and communication networks.

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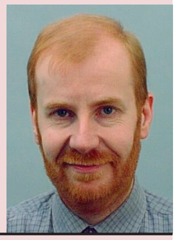

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