Experiments of Ana4: An Implementation of a 2.5 Framework for Deploying
Real Multi-hop Ad hoc and Mesh Networks

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Abstract

We consider the problem of interconnecting several hosts in a spontaneous hybrid network, i.e. an environment where wired and multi-hop wireless technologies are used. Dealing with the issues raised by such hybrid networks and addressing all the challenges listed in MANet may require a departure from classical solutions available in the literature. To enable a full multi-hop connectivity without raising problems/inconsistencies regarding IP compatibility, we have proposed Ana4, a 2.5 layer architecture suitable for hybrid networks. In this article, we present the advantages of Ana4 in the context of ad hoc and mesh networks as well as application fields where Ana4 is already used. We also present experimental measurements that show good performances with respect to a full IP solution (IP routing) and similar 2.5 approaches like MPLS.

1. Introduction

Wireless communications will play a crucial role in ambient networks that will interconnect a wide range of equipments, from places like homes and offices to public areas. Such ubiquitous computing will undoubtedly interconnect a set of heterogeneous equipments (personal electronic devices, video entertainment, play station, home appliances) with several heterogeneous physical and link layer technologies, from wired to wireless ones. In such scenario, wireless devices may be fixed or not and one may imagine that all devices will take profit from a global Internet connectivity. Wireless technologies offer open solutions to provide mobility and services where the installation of a complex wired infrastructure is not possible. Nowadays, performance of wireless local area networks increases with the evolution of the normalized physical layers (802.11b, 802.11a, 802.11g, zigbee, wimax, ...).

Multi hops wireless ad hoc networks and mesh networks offer a promising application field as main actual wireless technologies used by personal devices operate only over short distances. Moreover, it may not be possible to always deploy a networking infrastructure (cellular or wire cable) due to practical or cost constraints. In order to extend the coverage of classical wireless infrastructure-based networks, wireless multi hop networks (or wireless ad hoc/mesh networks) have been proposed.

In this paper, we present the implementation of a practical architecture suitable for interconnecting devices in an hybrid network environment, where wired and multi hop wireless technologies are used. By ad hoc architecture, we denote a set of rules and operations dealing with addressing and routing that must be set up for the ad hoc network to offer basic services such as routing, IP compatibility or Internet connectivity. In particular, such an architecture must answer the two following fundamental questions: what is an ad hoc address? What element is identified by an ad hoc address?

Previous works on ad hoc networks have mainly relied on the IETF MANet working group that proposes an architecture in which the basic element is the network interface and where an ad hoc address is an IP address. Under IPv4, the actual philosophy is to design/implement all MANet routing protocols at the IP level. This architecture is not fully satisfying and introduces several issues/inconsistencies regarding IP
compatibility. As ad hoc packets are routed using IP addresses, there is a chicken and egg problem while dealing with IP address auto-configuration in a multi-hop environment: under the MANet philosophy, in order to perform multi hop communications an IP address is mandatory but it the same time, to obtain an IP address from a DHCP server located several hops away, an host need to perform a multi hop communication. Regarding this architecture, IP broadcasting in an ad hoc network is also a hard task as the IP broadcast address must not be routed/forwarded. Moreover, it is important to notice that, as stated in [4], a MANet node using wireless technologies A and B (e.g. frequency A and frequency B) can communicate with any other node possessing an interface with technology A or B. This means that the ad hoc routing must operate over a multi-graph composed of several physical graphs and that an ad hoc node is the union of all its interfaces involved in the ad hoc network. This view increases the routing complexity and the number of control messages when several interfaces of a same ad hoc host are identified by different ad hoc addresses as it is the case in the MANet philosophy. Addressing all the challenges listed in MANet [4] may require a departure from solutions available in the literature. Implementing the ad hoc support below IP is not new. In the past, several architectures have been proposed: LUNAR [12], ABR [11]. More recently, a solution called Lilith for spontaneous networks based on MPLS [13] has been proposed. We will see that all these architectures lack flexibility to be completely satisfying.

In this paper, we present Ana4 [1] an underlay networking mechanism useful for MANETs. Ana4 defines a new generic lightweight and efficient ad hoc architecture, which relies on the notion of ad hoc virtual interface and logical sub-networks. A virtual interface is a logical entity which abstracts a set of network devices into a single addressable network component. In this paper we focus on the architecture and on the implementation and performance measurements of our 2.5 proposal for multi hop hybrid networks. The rest of the paper is organized as follows. We first discuss in section 2 the services that we can legitimately expect in an ad hoc network. In section 3, we present the related works and describe our Ana4 architecture. Then we briefly expose some advanced functionalities of Ana4 in section 4. Section 5 is dedicated to several actual use of Ana4. In section 6 we present some measurement experiments. Finally, we conclude this article with section 7.

2 Plea for an ad hoc architecture

The fundamental service in an hybrid environment is to allow communication between all devices of the network, that is, to able a peer-to-peer mobile routing capability in a purely wireless domain as stated in [4]. Since some nodes may be out of range or since some nodes may not share the same medium (incompatible wireless devices), it is necessary to define complex routing mechanisms that allow multi-hop routing. Inside a given hybrid network, routing mechanisms must be implemented in order to guarantee the intranet connectivity. These mechanisms must ensure unicast and broadcast/multicast routing capabilities. Some other services are also required, such as support for the TCP/IP protocol stack or Internet connectivity. In this section, we give a brief and not exhaustive overview of the main services that one can legitimately expect in an ad hoc or mesh network.

Intranet connectivity. The routing paradigm is the main factor driving the design of all networks. The routing function problem in ad hoc network appears as a crucial point and specific routing algorithms must be derived for ad hoc network. Several researches are done both on proactive and reactive approaches. It is important to notice that, as stated in [4], a MANet node using wireless technologies A and B (e.g. 802.11 and Bluetooth) can communicate with any other node possessing an interface with technology A or B. This means that the unicast routing algorithm must operate on a multi-graph composed of several physical graphs and that an ad hoc node is the union of all its interfaces involved in the ad hoc network. The unicast routing must offer a global connectivity over all the interfaces. The second important service that must be supported in an ad hoc network is the broadcast facility. As in classical networks, a node may need to send a message to all other nodes. This facility is used in almost all unicast routing algorithms [8, 10] developed for MANet networks and must be supported in an efficient way at the ad hoc level.
Complete support for TCP/IP. Once the connectivity is provided, the second service that must offer an ad hoc network is the TCP/IP one as the whole Internet relies on these protocols. Every node must be able to behave as if it belongs to a standard IP network, that is in "an interoperable inter-networking capability over a heterogeneous networking infrastructure”. Moreover, a partial support or compatibility with IP is an unsatisfying approach. Based on these trivial remarks, we must focus on the consequences they imply. First, IP defines a set of addressing as well as address-related routing rules. For example, it defines the notion of IP networks and IP sub-networks. Routing and accessibility directives are associated to these notions. IP also proposes broadcast notions and rules. For example, a packet directed to the address 255.255.255.255 is received by all nodes connected to the local link of the source and is not supposed to be forwarded. Numerous protocols and applications rely on IP standards. If we desire a complete compatibility with existing networking environments, the ad hoc architecture must be fully compatible with IP. Secondly, several auto-configuration mechanisms are proposed in association to IP. In IPv4, the DHCP protocol allows an host to retrieve its IP address from a server. If these services are powerful ones in wired networks, their importance is also obvious in ad hoc networks.

Internet Connectivity. In an hybrid context, it is important to offer a global connectivity. The notion of global connectivity is more general than the care of address feature present in IP mobility or the delivery of a global IPv6 address. Offering a global connectivity to the Internet is providing a service continuum. This means for example that an ad hoc node must be able to receive its favorite net-radio multicasted from a server which is not localized within the ad hoc network. As stated above, the multicast protocol used inside the MANet will be specific and the global connectivity service will perform the gateway operations with PIM/CBT/YAM...

Other features. We may want to be able to switch from one physical radio interface to another for power consumption reason for example, without interrupting its sessions or having to deal with any IP mechanism. It means that a micro-mobility (or vertical mobility) support must be implemented inside an ad hoc node so that changing its ad hoc communicating interface will not lead to a change in the IP address used by the host. An other very important feature is the easiness of implementation. Turning a node (PC, PDA...) into an ad hoc node should not require any kernel modification nor any driver modification. Last but not least, the scalability requirement may be an important factor. One can imagine than an ad hoc network may support tens to hundreds of mobile nodes but must also be scalable to a higher factor if this kind of networks becomes really pervasive [7].

3. The Ana4 Architecture

Based on the preceding remarks, it seems important to provide a more fine grain layering that includes an ad hoc level as compared to the pure IP layering. We can locate it at level 2.5, i.e., between level 2 (MAC) and level 3 (IP). Locating the ad hoc level at layer 3 induces several problems with the IP protocol as it is currently known. We argue that in order to be able to deploy ad hoc networks in a very friendly way, a full IP stack support must be provided which also implies to take into account the legacy of already deployed applications/configurations. Likewise, locating the ad hoc level at layer 2 like for the LUNAR [12] architecture induces several issues concerning multiple interfaces support and hardly enables support for micro-mobility. For instance, LUNAR does not address the support of multiple interfaces. Moreover, LUNAR is bound to a specific routing scheme and has been designed for small networks of around 10 to 15 nodes.

Locating the ad hoc layer at level 2.5 is an interesting alternative as it can both enable a full support of IP and provide the opportunity to handle several interfaces. A first step towards this direction was made with an implementation of ABR [11]. However, ABR relies on the IP addressing which leads to the already described auto-configuration issue and, as LUNAR, is bound to a specific routing scheme. Recently, a work posterior to Ana4, Lilith [13] was designed to use MPLS for ad hoc routing. However, this solution is also not satisfying as it does not support multiple interfaces or vertical handoffs, the handling of logical sub-networks or auto-configuration mechanisms and since it is binded to a on purpose proactive like routing pro-
3.1 Inter-node architecture

We propose an architecture breaking up an ad hoc network into three levels of abstraction: the hardware level, the ad hoc level and the IP level. If the first one relies on a physical reality, interface communication compatibility, the two others are purely theoretical views. The base element of the first level is the wireless interface whereas for the two others, it is the ad hoc node. Our definition of an ad hoc node follows the one proposed by MANet in [4].

Hardware level. The hardware level is the set of the different hardware networks. A hardware network is the gathering of all interfaces that are physically able to communicate with each others. At this level, the notion of communication ability is related to link layer device compatibility and not to effective communication possibility. In a hardware network, hardware addresses (e.g., MAC) identify interfaces.

Ad hoc level. The ad hoc level defines the ad hoc network. An ad hoc network is the combination of all hardware networks. At this level, the base element is no more the interface but the ad hoc node. We do not make distinction between interfaces but only see nodes with a single interface, the ad hoc virtual interface connected to the ad hoc network. A unique ad hoc device is abstracted from all wireless and wired devices. In an ad hoc network, an element is named using a unique node identifier, also called an ad hoc address. Multi-hop communication is available. One node may send packets to a node distant from several hops. Packets are commuted from ad hoc nodes to ad hoc nodes depending on the ad hoc addresses of destinations. Broadcast and multicast mechanisms are also available. While commuted, a packet may transit through any underlying hardware network and join the destination through any of its hardware interfaces. The followed path is determined by the commutation or routing protocol. This particular architecture is interesting since it does not require any modifications neither in device drivers nor in the TCP/IP stack.

IP level. At this level, an ad hoc network is seen as an Ethernet bus (more precisely as a switched Ethernet link): the IP abstracted network. An ad hoc node of the ad hoc level is looked upon as a single and classical Ethernet interface: the virtual ad hoc interface. In other terms, a node with several physical devices only owns one interface from the IP view. All the commutation work performed at the ad hoc level is transparent to IP.

This architecture allows a complete compatibility with IP. For example, locally broadcasted packets reach all nodes of the ad hoc network without being IP routed. Auto-configuration becomes straight-forward. Retrieving an address at multiple hops through the DHCP protocol is possible since ad hoc nodes are reachable even if not IP configured. As the commutation is performed at the ad hoc level, no IP address is needed to communicate with other ad hoc nodes. More globally, all the IP world behaves as it does with an Ethernet link.

3.2 Intra-node architecture

The role of a virtual ad hoc interface, illustrated in figure 1, is to hide the different physical devices and hardware networks; it provides the illusion of a single virtual network. At the ad hoc level, this virtual network is a wireless multi-hop network; at the IP level, it is a switched Ethernet link. A powerful characteristic of this architecture is to allow an host to use a device simultaneously in ad hoc and in classical modes. Suppose that a physical device handled by a virtual ad hoc interface is also configured as an Internet device. From the IP view, the mobile hosts two distinct interfaces. IP networking is performed over these two interfaces without interference.

The virtual interface. For upper layers, the virtual interface acts as a classical interface. For example, it is declared as an Internet device to the IP layer. IP outputs packets directed to ad hoc nodes through the virtual interface. For the under layer, i.e. the link layer, the virtual interface acts as an upper layer protocol. Upon reception of a packet that has transited through the ad hoc network, the packet is given to the virtual interface. This particular architecture is interesting since it does not require any modifications neither in device drivers nor in the TCP/IP stack.
Naming ad hoc interfaces. Introducing a logical network and logical interfaces requires the introduction of a corresponding logical naming process. Virtual interfaces are addressed using ad hoc addresses. An ad hoc address is composed of two fields (Fig 2): the network identifier field, Net Id, and the node identifier field, Node Id. The last field must ensure the uniqueness of the ad hoc address. It may be configured by hand, chosen using a MAC address or using a statistically unique and cryptographically verifiable (SUCV) identifier as presented in [9]. SUCV identifiers allow authentication of ad hoc nodes in the network.

Figure 2. Structure of an ad hoc address

3.3 Commutation

The role of the virtual interface is to commute packets between different devices and upper layer protocols. Upon reception of a packet, the interface decides whether it has to emit the packet, through which interface and to which nodes, and whether it has to forward it to upper layers. A virtual interface owns a commutation table. This table is managed by an application level routing protocol such as the ones studied in the MANet group (OLSR [8], AODV [10] or DSR [6] for example). The routing protocol is independent of the global architecture. Any MANet protocol may potentially be used. Its role is to compute or discover routes and to configure commutation tables in ad hoc interfaces. Very few work is required to adapt a MANet routing algorithm to our architecture. Basically, node identifiers have to be changed from IP to ad hoc addresses.

4 Advanced functionalities

As we have already said, our architecture intrinsically provides a multiple interface support and allows the use of different network protocols over the ad hoc network. Ana4 is an architecture that allows a complete support for IPv4, including auto-configuration mechanisms. It also provides a complete connectivity with the Internet, in regards to routing but also multicast and other services mechanisms. Moreover, Ana4 handles problems related to scalability and network partitioning. Trying to keep a totally flat topology may induce too long flooding delays or huge routing tables. The network identifier field of an ad hoc address allows the setup of sub-ad hoc-networks through the introduction of communication policies between ad hoc nodes with different network identifiers. Ad hoc networks can be split in several logical subnetworks which will appear to IP as different virtual Ethernet links. For more information on Ana4, its functioning or its advanced functionalities, please refer to [2].

5 Deployment of Ana4

Ana4 is currently used in 4 different test beds, two of them in partnership with private companies.

Classical mesh network research test bed. The first “simple” scenario is to use Ana4 to set up a wireless mesh network test bed using an ad hoc routing protocol such as OLSR. By mesh network, we assume a network composed of some fixed and mobile nodes, wireless and wire links and that handles many-to-many connections and is capable of dynamically updating and optimizing these connections. The dynamic management of complex routing information that includes information about external networks (e.g. the whole wide Internet and the gateways to it), is one important key feature inside our research lab mesh network. By
deploying 10 shuttle PCs in the lab, some of them connected to the Internet via a wired link, and by configuring several laptops we are able to use this hybrid network as a regular wireless office covering network. We can come up with relevant real-world scenarios where hybrids between "static" and "ad-hoc" networks offer some clear advantages – networks where a number of static nodes form the matrix (the substrate) in which other nodes appear, roam, and disappear. In this mesh network, auto-configuration of mobiles is performed using DHCP.

**Heterogeneous seismic sensor network.** The IHR [5] project is the second test bed using Ana4. The ambitious goal of the IHR project is to develop a new seismic tool that would allow seismic investigation at scales comprised between one kilometer and few hundreds of meter. The geological targets are those potentially dangerous areas: fault zone, volcanoes, land-slides, valley with site-effect. A new equipment has been recently delivered. The new seismic network consists of thirty nine channels data-loggers equipped with six vertical sensors plus one component sensor. These spider-like mesh networks are connected to each others by network links (wire when possible and/or wireless) that allow a limited crew to control and tune the 270 channels. The deployed seismic network is heterogeneous and scientists on the field encounter several pure networking problems when they try to manage this spider network. How to configure the wireless network, the wire backbone network? How to deal with IP sub networks... Ana4 offers a simple solution. Due to the Ana4 support for multiple interfaces, the ad hoc network is spread over both the wireless and wire links, hiding the complex and heterogeneous topology to the end user. Auto-configuration is also made straight-forward as the retrieval of an IP address is possible even if nodes are several hops away from the DHCP server. In order to manage the seismic network, scientists also perform broadcast operations in order to start/stop all data loggers. Once more, there is no need to modify all specific application dedicated to the control of the seismic sensors as Ana4 offers a real broadcast to the IP layer even if packets are doing multi hops at the ad hoc layer.

**Video Billboard.** Those who communicate messages are always in search of attractive ways to carry their information more effectively. When placing outdoor advertising campaigns, 30-second television commercials on large screens (14.69ft x 11.02ft), displaying advertisements, video footage and general information on buildings and walls in busy metro, market, restaurant and/or nightlife districts, the main problem is to carry the messages and update the information. The key idea was to use Ana4 to build a “video billboard mesh network” in order to perform content delivery and network management without deploying a wired network. It’s always more easy to get a power supply on outside building wall than a RJ45 like plug. This project is in partnership with the Embedia company. Embedia is an interactive communications solutions provider. Embedia creates an innovative state-of-the-art link between businesses and their consumers and its patented solution delivers interactive multimedia content directly to end-user devices.

**Inventory control and localization.** In many industrial contexts (logistics, objects and people monitoring, security...) it may be essential to localize precisely objects or people in real time, whether they are situated indoor or outdoor. In this goal, Kadya is working on providing a localization solution based upon cheap and light emitting radio tags, monitored by a set of listening stations. Each station collects data emitted by the tags through a proprietary radio protocol, and reemits them through a mesh network to a server which analyzes the radio data to calculate the position of each radio tag. Ana4 is used to provide the illusion of a one hop IP network, allowing use of DHCP and broadcast operations for the listening stations. Moreover, the system is easily extensible as any additional station can be placed in the mesh network without the need for any configuration as the multi-hop connectivity is achieved by Ana4 and the IP configuration by DHCP. Furthermore, Ana4 allows the use of IP broadcasting over the network to monitor the system.

6. Performance

We have implemented Ana4 as a kernel module and the code has been released\(^1\). The first implementation

\(^1\)http://www.sourceforge.net/projects/ananas
was done under Linux (PC and PDA) and Windows XP. We provide more details on the implementation in [3] and we summarize below some performance results based on analyses and measures in an experimental network of Ana4 nodes.

![Figure 3. Effective bandwidth ratios on the y-axe as a function of the transmitted packet size (in bytes) on the x-axe.](image)

First, we show the theoretical overhead of Ana4. The Ana4 header introduces an overhead of 160 bits in all packets transiting in the ad hoc network, reducing the performance the network may achieve. However, this overhead is not significant. First, it does not much reduce the volume of data a packet may include. 160 bits is less than 0.8% of a 802.11 link transfer unit (TU: 2312 bytes). Second, this overhead does not much lower the useful bandwidth of the medium. It only takes 14us to transfer 160 bits over a link with a 11Mbits/s throughput. In the 802.11 technology, this delay is 8 times smaller than the delay awaited before accessing the medium (DIFS = 128us). Figure 3 presents some theoretical bandwidth ratios. The medium is a 802.11 link with 11Mbits/s throughput. The x-axis is the size of data in the exchanged packets. The y-axis is the ratio between the effective bandwidths with and without Ana4. The two plots correspond to a classical RTC-CTS-Data-ACK transfer scheme and a Data-ACK one. In the worst case, packets with only 1 byte of data, the overhead is very low, only 7% loss of the effective bandwidth.

![Figure 4. Experimental platform.](image)

To evaluate our Ana4 prototype, we measured its performance in a multi hop network composed of a 4 nodes chain connected via 802.11b wireless or wire links (Fig 4). The goal is to measure the round trip time (ping) and the throughput (netperf) between nodes at distance 1, 2 and 3 hops (i.e., between nodes: A − B, A − C and A − D). The comparison was done between: (i) a pure static IP route scheme which may be considered as the reference when implementing ad hoc network at layer 3, (ii) MPLS commutation with MPLS linux\(^2\) which may also be considered as a reference when implementing an ad hoc solution at layer 2.5 and (iii) our Ana4 implementation.

<table>
<thead>
<tr>
<th>Case</th>
<th>(i) static IP</th>
<th>(ii) MPLS</th>
<th>(iii) Ana4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 hop: A − B</td>
<td>0.099ms</td>
<td>0.114ms</td>
<td>0.115ms</td>
</tr>
<tr>
<td>2 hop: A − C</td>
<td>0.183ms</td>
<td>0.206ms</td>
<td>0.222ms</td>
</tr>
<tr>
<td>3 hop: A − D</td>
<td>0.272ms</td>
<td>0.298ms</td>
<td>0.326ms</td>
</tr>
</tbody>
</table>

Table 1. Latency comparison in a wire environment. Average on 100 ping measures with a 64 byte data payload (on top of IP).

Table 1 presents the result of the latency measurements with wire links. The reasons why we used wire links for this measurements is to minimize the medium transmission time in order to isolate the overhead caused by the Ana4 or MPLS layer. We can observe that the overhead introduce by Ana4 is very low. In this overhead, one part is caused by memory operations (introduction and deletion of the Ana4 header). This part can be observed in the one hop measurement. As we can see, this setup cost is equivalent for Ana4 (0.115ms) and MPLS (0.114ms) as both protocols perform equivalent operations with their respective headers. The rest of overhead is due to computations (routing table interrogation), at each hops. For this last part, MPLS achieves a better performance (0.092ms/hop for MPLS vs 0.105ms/hop for Ana4) even if the difference is quite negligible (0.013ms). The reason for this is that the MPLS header (32 bits per label pushed in the MPLS label stack) is smaller than the Ana4 one and that the MPLS code is highly profiled and designed for high performances which was not the case with the Ana4 prototype. We are confident on the fact that we could achieve similar results as MPLS with a profiled Ana4 code.

\(^2\)http://sourceforge.net/projects/mpls-linux/
Table 2. Throughput comparison (netperf) in a wireless environment.

Table 2 presents the result of bandwidth performances in a wireless environment. The bandwidth was measured using the netperf software. In the worst case, 1 hop, Ana4 induces a bandwidth lost of 3%. This time, the overhead decreases with the number of hops. The reason for this is that the computation overhead at each hop is recovered by the communications during the transfer. As a consequence, the highest the number of hops, the most negligible it becomes. As for the latency, the difference between MPLS and Ana4 is due to the headers size and the code profiling.

7. Conclusion

We have presented Ana4, a practical architecture suitable for interconnecting devices in hybrid network environments. Our goal is to provide a generic lightweight and efficient ad hoc architecture, which relies on the notion of ad hoc virtual interfaces and logical sub-networks. Ananas defines an ad hoc network by introducing three levels of abstraction: the hardware level, the ad hoc level 2.5 and the IP level 3. By designing an ad hoc level at layer 2.5, actual ad hoc routing protocols can be implemented and advanced features like sub-networking, vertical handover or auto-configuration can be offered.

Our first implementation under linux and windows XP shows good performances compared with traditional IP routing and/or MPLS commutation. We observe only a small degradation for the latency and a very small overhead for the throughput when using the Ana4 architecture. However, and as stated before, Ana4 offers advanced features like sub-networking, auto-configuration, vertical handover or all ad hoc node broadcast...

Several possible extensions for this work are open to investigation: taking into account the energy consumption of interfaces to switch from one to another under the virtual ad hoc interface in order to provide the best ratio between energy and throughput for a given class of traffic; auto-organizing the network using the ad hoc sub-network possibilities. Last but not least, we still work on the performance experiments, on the Ana4 code profiling and on the deployment of Ana4 in several scientific or industrial real test beds as mentioned in this paper.

References