MANET perspective: current and forthcoming technologies

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***Abstract*— In this paper we present experimental results of an innovative testbed on a 23 nodes MANET with particular attention to routing and middleware performance. Specifically, a proactive and a reactive routing protocol have been analysed before experimenting a new optimised p2p system based on cross-layer interactions with a proactive routing protocol. The experimental analysis on this medium-scale MANET has been carried out in the framework of the IST-FET MobileMAN project. It shows that the proactive approach does not negatively influence system performance, even better it supports upper-layer protocols sharing complete network topology information. Thus, the p2p system drastically reduces the network overhead, and it correctly manages network partitioning. However, current technologies are not suitable to support large-scale MANETs characterized by intermittent connectivity or in need of an Internet connection. For this reason in the last part of the paper we move our focus towards forthcoming technologies such as Mesh and Opportunistic networks, that introduce new communication paradigms paving the way to innovative applications.**

I. Introduction

In the last decade the MANET research community has been very active producing a huge quantity of protocols belonging to different layers of the stack [1]. Results have been mainly validated through simulative studies. However, some real-world measurements [2] [3] highlithed that often simulations results turn out to be quite unreliable, introducing simplifying assumptions that mask important characteristics of real protocols behaviour. For this reason, real-world experiments are highly required, even if they are costly, in terms of time to set up and management of high number of nodes. In the framework of IST-FET MobileMAN project [4] several measurement studies have been conducted [5] [6] [7]. Specifically, we focused our studies on a full ad hoc network protocol stack, from the physical layer up to the application layer, comparing performance results of a legacy-layer architecture with those of a cross-layer architecture [8]. A prototype of the cross-layer architecture limited to middleware and routing interactions has been developed and tested pointing out its advantages [6]. In this paper we report our experiences and results obtained by measurements on a real MANET of 23 nodes, as extension of our previous work on a smaller scale network [6]. The cross-layer architecture confirms to be more efficient than the legacy one, since it drastically reduces the overall network load, and provides a quite more stable and responsive network environment. Thus, we highlight advantages and drawbacks of current network architectures, taking a glance at forthcoming technologies such as mesh [9] and opportunistic networks [10]. The paper is organized as follows. Section II presents the testbed architecture and experimental environment. The methodology of experiments and the performance analysis is reported in Section III. Finally, emerging technologies are discussed in Section IV.

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II. Testbed architecture and experiments environment

Only few measurements studies on real ad hoc testbeds can be found in literature and they generally focused on a single layer of the MANET architecture, with particular attention to routing protocols ([11] [12] [13] [14]). In the framework of the MobileMAN project [4] we deployed various experimental testbeds from small-scale to medium-scale MANETs, involving up to 23 nodes. Initially [7], the activity focused on a small ad hoc network. At the network layer, we compared the reactive AODV ([15]) and the proactive OLSR ([16]) routing protocol in terms of traffic generation and configuration delay in static and low-mobility scenarios [6][7]. At the middleware layer, first we evaluated a p2p system based on a Distributed Hash Table (Pastry [17]), developed for the wired network, on top of the selected routing protocols. Then, we analysed a cross-layer p2p system for ad hoc networks (CrossROAD [18]), based on the main principles of Pastry, but optimised through cross-layer interactions with a proactive routing protocol. We compared the two p2p systems pointing out advantages of our solution. The novelty of this work is represented by results obtained by a 23 nodes testbed, even though we mainly consider static scenarios. All the experiments have been executed inside the CNR campus in Pisa, mixing indoor and outdoor connections. To develop a multi-hop ad hoc network with 23 nodes in a small geographic area, physical characteristics of the building and heterogeneous transmission power of wireless cards were exploited to obtain a redundant topology with realistic wireless links based on 802.11b. Taking into account the environment constraints we identified the initial positions of mobile devices fixing the transmission rate at 11Mbps and hence the starting topology of our MANET as shown in Fig.1. To deploy such a high number of laptops in the campus, several students of Computer Engineering from the University of Pisa have been involved in

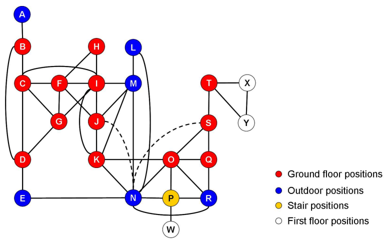


Fig. 1. Network Topology

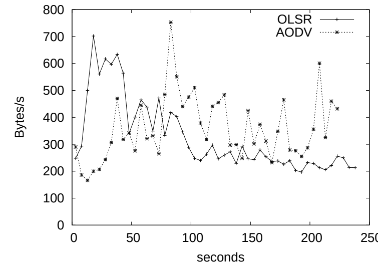


Fig. 2. Average overhead introduced by OLSR and AODV

this experimentation. Thus we were able to better understand the impact of this technology on a set of skilled users [4].

A. Prototype Architecture

As in our previous work, here the analysis of the network layer focuses on OLSR and AODV as routing protocols, running two different types of traffic on top of them. More precisely, during the experiments we used the simple `ping` utility to evaluate delays and packet loss. Instead a distributed application on top of a p2p system has been used to measure the overhead introduced by routing protocols in case of a more realistic scenario involving a complete MANET architecture.

At the middleware layer, performance analysis of Pastry running on a MANET [7] demonstrated that this kind of p2p systems introduces a big overhead due to the construction and management of its internal data structures. For this reason a new optimised solution, named *CrossROAD*, based on a cross-layer architecture, has been developed [18]. Specifically, it inherits all basic principles of the Pastry model that defines a subject-based routing policy scalable with the number of peers. In addition, it optimises the overlay construction and management on ad hoc networks by exploiting cross-layer interactions with a proactive routing protocol. Specifically, CrossROAD defines a new Service Discovery protocol that associates a unique identifier to each application running on top of it, and this information is broadcasted on the network piggybacked into routing packets. Thus each node can autonomously build the overlay collecting the list of partecipants from the proactive routing protocol. A detailed description of the system implementing these cross-layer optimisations can be found in [6]. Due to the limited space in this paper we mainly focus on experimental results. To compare and contrast the Pastry model with our cross-layer enhancements, we developed a simple Distributed Messaging (DM) application that can run on top of the two systems. Nodes running DM set up and maintain an overlay network related to this service. Once a node has created/joined the overlay, the application provides the possibility to create/delete one or more mailboxes, distributed on the other nodes, and to send/retrieve messages to/from them.

III. Experiments and performance evaluation

In order to obtain a complete performance evaluation of the entire system, several set of experiments had to be executed. Hereafter we first focus on routing results and then on middleware results.

A. Routing performance

In this section we present the performance evaluation of OLSR and AODV in static scenarios, focusing on the following parameters: *i)* the network overhead introduced by routing messages; *ii)* the packet loss suffered at the application level; *iii)* the delay measured during data transfer.

To evaluate the routing overhead we consider an experiment involving not only the routing layer but also the p2p system. In this way, the traffic generation on top of the routing protocols is more complete than a single `ping` utility due to the presence of TCP and UDP connections. This results in a more realistic evaluation of the bandwidth utilization. In this experiment, all nodes started running the routing protocol at the same time (see Fig.1). After 30 seconds needed for the network stabilization, each node joined the overlay using a random sequence maintaining the Pastry overlay for 4 minutes. The join procedure does not require the communication between each pair of nodes. Fig.2 shows the total overhead introduced by OLSR and AODV as a function of time. The curves are obtained averaging the total control traffic generated and forwarded by each single node over the number of nodes taking part to the experiment. As it clearly appears from the picture, OLSR and AODV have different behaviors. Specifically, OLSR introduces a higher overhead during the starting phase (600 Bps) to establish the complete network topology. Then after a period in which its traffic load coincides with AODV load (400 Bps), OLSR performs better for the rest of the experiment (250 Bps). In fact, AODV peaks of traffic are mainly due to several discovery procedures to maintain the overlay network. However, in an overall view the overhead of both protocols falls in a range of [200, 700]Bps, confirming that, also in medium-scale networks, they do not negatively affect system performance. A detailed analysis of the overhaed related to each node can be found in [19].

Referring then to performance evaluation of the routing protocols in terms of overall packet loss and delay suffered in the network, we simplified the proposed scenario using a lighter data traffic as the ICMP traffic. In fact, the Ping utility is sufficient to measure the RTT for a connection. As in the previous experiment, in the first 30 seconds the routing protocol ran alone. Then, each node started pinging all the others using a random sequence. Each ping operation, generating 1 pkt/sec, lasted for 1 minute. At the end of the sequence they kept running the routing protocol for the last 30 seconds. The whole experiment took 23 minutes. To evaluate the overall packet loss suffered at the application level, we averaged all Ping operations between couples of nodes at *x*-hop distance. Table I shows the percentages obtained for different number of hops. Looking at the results we can

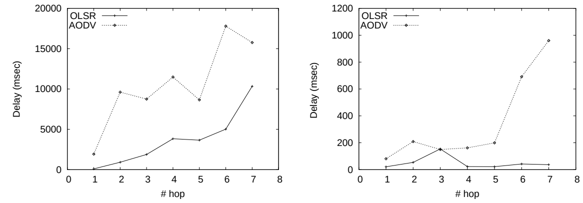
	1	2	3	4	5	6	7
AODV	20%	51%	51%	61%	67%	86%	89%
OLSR	5%	15%	28%	35%	45%	52%	67%

TABLE I

OVERALL PACKET LOSS FOR DIFFERENT NUMBER OF HOPS

notice that OLSR performs better than AODV. In particular, OLSR delivers almost all packets at 1-hop distance, suffering a packet loss of [15%, 45%] for nodes distant [2, 5] hops. Finally it delivers less than 50% of the application traffic with connections of 6-7 hops. On the contrary, problems with the reactive protocol are more evident. AODV does not properly work even nearby, achieving 20% packet loss even at 1 hop. Its performance further decreases to 50% at a distance of 2-3 hops, drastically degenerating (more than 85%) beyond 5 hops. In the 3-hop indoor string topology analysed in [5], OLSR performance was acceptable in all Ping operations towards each node in the string, instead AODV lost 50% of ICMP packets while communicating with nodes at 3-hop distance. In this medium-scale environment, for both protocols we observe greater percentages of undelivered packets also with few hops. Possible explanations of these results are the different network size (small vs. medium) and the complexity of the experiment (1 Ping operation vs. 23 simultaneous Ping operations). In particular with concurrent connections each node can act as a destination for a Ping operation and also as a router for another one. Thus the probability of MAC collisions is considerably increased causing also several route failures.

Finally, to evaluate the delay introduced by the routing protocols, we measured the end-to-end latency for completing a Ping operation between couples of nodes. In particular, we focused on: *i)* the average delay to deliver the first successful ICMP packet to a selected destination; *ii)* the average delay to deliver all the other packets of the ping operation. Each value is averaged over couples of nodes distant *x* hops. Fig.3a and b show the obtained results. As it clearly appears in Fig.3a, as expected, the OLSR curve is lower than the AODV curve due to the different nature of the routing protocols. Specifically, the OLSR curve increases almost linearly up to 6 hops, and then it doubles at 7 hops. This is mainly due to the network instability that implies some topology reconfigurations and the consequent increase of delays. On the contrary, AODV curve is a step function. It needs about 2 seconds to discover routes to 1-hop neighbours, about 10 seconds for nodes in the range of 2-5 hops distance, and finally [15, 17] seconds to discover valid paths towards nodes distant 6 hops and more. These high delays are due to several attempts performed in the route discovery process. In fact, we have seen that each node makes about 5-6 attempts in order to discover a valid route to its destination. Looking at Fig.3b, note that OLSR requires delays in the range of [20, 60] msec independently of the number of crossed hops, while AODV introduces higher delays [200 msec, 1 sec]. Form the log files of the experiments we noticed that AODV is not able to maintain the first discovered path to the same destination for the entire connection, requiring 1 or 2 attemps to re-establish a valid route to the destination. This



(a) Average Delay on the first successfull ICMP packet.

(b) Average Delay on delivered packets.

Fig. 3. Average Delay suffered by OLSR and AODV for different number of hops.

is the main reason of low performance of AODV.

We also analysed some mobile scenarios with nodes changing their positions. In these cases, even though OLSR is slower than AODV to propagate networks' changes, it discovers more stable routes and delivers higher percentages of application data (for details see [19]).

B. Overlay network performance

In the middleware experiments we compared CrossROAD and Pastry in static and mobile scenarios. In static scenarios we mainly analysed the overhead introduced by the overlay management on the network in terms of traffic load and delay. We mainly considered a particular experiment in which every node generated an application message every 100 msec for 120 seconds. In a prior phase lasting 30 seconds the routing protocol ran alone to stabilize the network topology. We defined the average traffic as the aggregation of the overlay management traffic, the application data traffic, and the routing traffic sampled every second and averaged over the number of network nodes. Considering the routing traffic together with the overlay and application traffic is important in case of CrossROAD. In fact, on the opposite of Pastry, CrossROAD does not introduce additional overhead to maintain the overlay data structures at the middleware layer, but it exploits the routing protocol to distribute services information and locally compute the rest of the overlay. The average traffic load is shown in Fig.4 considering three different cases: CrossROAD, Pastry running on top of OLSR, and Pastry on top of AODV. As shown by the figure, the overhead introduced by Pastry is generally much higher than that of CrossROAD, either in case of OLSR or AODV. This is mainly due to periodical remote connections needed by Pastry to monitor the status of other nodes of the overlay and consequently update the overlay data structures. On the other hand, in case of CrossROAD, each node becomes aware of changes in the overlay directly from the cross-layer interaction with the proactive routing protocol.

Analysing Fig.4 in more detail, we can note that the average load is negligible for the first 30 seconds of the experiment compared to high values in the second part. In fact, nodes spent 30 seconds running only the routing protocol to stabilize the network topology. In this phase the AODV curve is the lowest one since AODV only sends Hello packets to discover 1-hop neighbours, while OLSR even in case of CrossROAD coincides with the original protocol since the p2p system is not yet active. On the other hand, from 30 to 90 seconds, the aver-

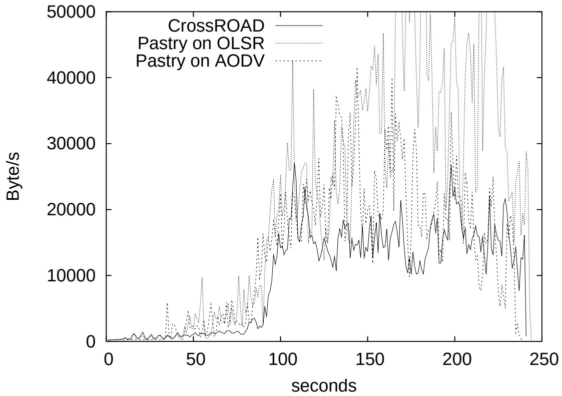


Fig. 4. Average aggregate traffic

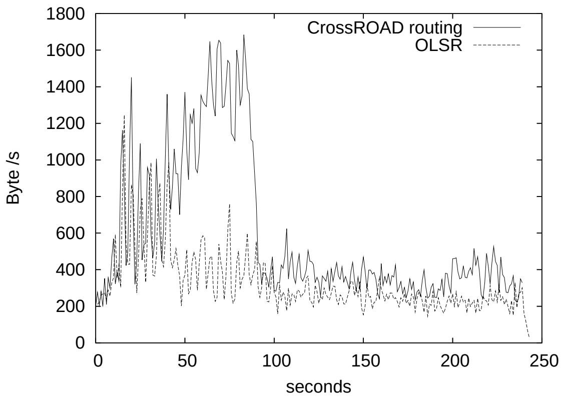


Fig. 5. Proactive Routing traffic

age load increases. In this phase nodes exchanged information required to build the overlay from scratch. In case of Pastry, each node needs to bootstrap from another node already in the overlay, thus generating peaks of about 6KBps. In case of CrossROAD, the traffic load is about 60% higher than legacy OLSR (see Fig.5), since nodes started running the system and they sent and received services information inside routing packets. After this phase, the overhead of the enhanced routing protocol approaches to the same values of OLSR, considering the periodic sending of service information on the network with the same frequency of Hello packets. For this reason, in the rest of the experiment CrossROAD overhead corresponds to the data traffic load introduced by the application, since the overlay management cost is almost negligible. Instead, in case of Pastry, the overlay management is much higher than the data traffic load, identified by CrossROAD in Fig.4.

Another important advantage of CrossROAD is the complete self-organisation of the overlay. In fact, analysing several experiments [19], we noticed that frequent failures during the Pastry bootstrap procedure caused several partitioning of the overlay. On the other hand, CrossROAD constantly maintains a single overlay in static scenarios. More specifically, when running Pastry on top of OLSR and AODV, we got respectively four and five overlays. This depends on connection failures due to the absence of a route to the destination or to the instability of the selected link, and it influences the entire experiment.

Considering the average delay measured by nodes to send a specific message and receive the related reply (see Table II), we noticed that peaks of 100 seconds are measured in case of Pastry and a maximum of 60 seconds in case of CrossROAD, but the most part of them is concentrated on [0, 500]msec. To have a consistent view of delays distribution, only packets generated by nodes of the main overlay were considered (i.e. nodes that correctly executed the bootstrap procedure, joining the right overlay). In fact, in case of smaller overlays, delays are reduced to few milliseconds since the involved nodes have to manage only few packets. In addition, since the network topology is redundant and, in some cases, there are several unstable links, the distribution of data packets through TCP connections suffers many retransmissions, increasing the related timeout and transmission delay. In addition, in case of Pastry, processing data packets and managing overlay data structures further affects system performance.

Percentiles	CrossROAD	Pastry on OLSR	Pastry on AODV
$0,6$	$599msec$	$11.171sec$	$9.138sec$
$0,7$	$2.306msec$	$20.032sec$	$16.055sec$
$0,8$	$4.692sec$	$34.846sec$	$28.823sec$
$0,9$	$10.648sec$	$46.340sec$	$75.475sec$
$0,95$	$23.025sec$	$61.858sec$	$88.701sec$
$0,99$	$60.468sec$	$111.560sec$	$105.649sec$

TABLE II

DELAYS DISTRIBUTION

As the last set of experiments, we analyse a mobile scenario to evaluate CrossROAD performance to distribute data on the overlay nodes in terms of responsiveness of the cross-layer architecture to topology changes. Specifically, we consider a scenario in which central nodes in the network topology joined the network after the others. In this case nodes M and N, located as shown in Fig.1 (node L was not present in this experiment), started running OLSR and CrossROAD with a delay of 2 minutes after the others. Thus, the initial network topology consisted of two ad hoc networks (i.e., nodes A, B, C, D, E, F, G, H, I, J, and K form MANET1, while nodes O, P, W, Q, R, S, T, X, Y form MANET2). After the join of the central nodes, the two networks merged in a single one, as the two overlays did. Note that Pastry is never able to merge two distinct overlays into a single one. To better observe the system behaviour, during the experiment nodes A and Y generated periodic messages with random keys. As shown in Fig.6, they distributed data initially on nodes of their own overlay, and subsequently on all nodes of the network. This demonstrates the effectiveness of the cross-layer approach in a MANET, where supporting mobility and possible partitions should represent one of the main characteristics of network protocols.

IV. FORTHCOMING TECHNOLOGIES

Cross-layer optimisations presented so far are able to drastically reduce the network overhead, and thus improve MANETs scalability with respect to traditional, strict-layered approaches. Nevertheless, foreseeing very large, flat, networks of this type is not realistic. Current wireless technologies are not suitable to support multi-hop networks significantly larger than the one considered in this paper [12]. Furthermore, interconnecting MANET islands with the legacy Internet is not that easy. On one hand, some MANET nodes should be also connected to the wired Internet through nodes that act as gateways between the MANET and the Internet worlds. This

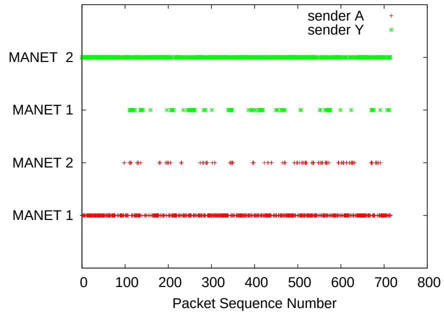


Fig. 6. CrossROAD data Distribution

approach requires the presence of costly Internet infrastructure close to the MANET, which is quite a limiting factor. On the other hand, some MANET nodes should be also connected to 2.5G/3G cellular networks, which would act as a bridge between the MANET and the legacy Internet. Though this solution requires less fixed infrastructure, it is very costly, and is not able to provide an acceptable bandwidth. We believe that a very promising direction to address both the MANET scalability and interconnection issues in a cost-effective way is represented by Mesh Networks [9]. Mesh Networks are multi-tier networks generally composed by three tiers. The first tier is represented by MANETs. Some node in each MANET is (wirelessly) connected to Wireless Routers, which represent the second tier. Specifically, Wireless Routers are static nodes (usually with more capabilities than MANET nodes) that form a mesh by establishing wireless links with each other. Finally, some Wireless Routers are connected to Access Points, which provide Internet access to the whole Mesh Network. Even though the Mesh paradigm includes some infrastructure (the Wireless Router tier), it is completely wireless, and can be built on top of open standards such as 802.11 or 802.16. Furthermore, Mesh Networks can deliver reasonable bandwidth to the end users and they are quite cheaper and more effective solution than the ones mentioned before. In the short/medium term, we envision this paradigm to be the most promising evolution of legacy MANETs. Nowadays, Mesh Networks are already used for intelligent public transportation and public safety, and system providing Internet access to rural and scarcely populated areas. On the other hand, in a longer time frame we envision Opportunistic Networking [20] as one of the most intriguing scenarios for MANET evolution. 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 for 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 brand-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. From a technical point of view, delivering information in such a network is really challenging. Legacy MANETs, like the wired Internet, assume that nodes have to be connected to the network in order to receive data. In an opportunistic paradigm, nodes must be free to be just *sporadically* connected to the network. Data generated while destination nodes are not connected must be stored inside the network, and eventually delivered once the destination connects. In addition, nodes will need to be more "intelligent" than legacy MANET nodes. Since the network topology is very dynamic and ever changing, it makes no sense to try to keep an up-to-date view of the topology at each node. Thus nodes will need to become self-aware of the environment they are operating in, to make sensible routing decisions. Such features are key to make Opportunistic Networks more scalable and usable than legacy MANETs. To this aim, within the framework of the IST-FET Haggle Project [10], we are investigating how to use situated autonomic mechanisms to support the Opportunistic Networking paradigm.

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