WIRELESS MESH NETWORKS: STATE OF THE ART AND RESEARCH DIRECTIONS

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ABSTRACT

Wireless Mesh Networks (WMNs) are currently becoming one of the most promising approaches to provide ubiquitous broadband Internet access. This paper provides a survey on recent advances and open research issues in WMNs. Network architectures and real world testbed are described, followed by some reference applications scenario. State-of-the-art protocols for WMNs are illustrated highlighting the most relevant research challenges. Finally, we report some performance measurements obtained on an experimental WiFi-based mesh testbed running at CREATE-NET premises. The tests aim at characterizing the suitability of current mesh networking solutions to support multimedia flows. The obtained performance is compared to those obtained by means of a conventional star-shaped topology based on the use of access points. The result show that mesh architectures are able to offer some advantages, in terms of fairness and lower packet loss rate, with respect to a standard access points based architecture.

KEYWORDS: Wireless Networks, Multimedia Applications, Multihop networks, Mesh Architecture, Performance Evaluation

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1 Introduction

As the trend toward broadband ubiquitous networking gains momentum, new networking paradigms are needed to fit the peculiarities of such novel scenarios. Wireless mesh networking has recently emerged as one of the most promising access architectural paradigms, being able to address a wide range of application scenarios, including home broadband Internet access, enterprise networking and metropolitan area networks [1, 2].

Wireless Mesh Networks (WMNs) rely on a multi-hop wireless backbone for delivering high-speed services to end-users without the need for deploying any fixed infrastructure. With respect to conventional star-shaped access network architectures, WMNs offer advantages in terms of enhanced robustness (in that no single points of failure are present and redundant links are encompassed) and flexibility (without the need for deploying cables, connectivity may be provided only where and when needed/economically attractive). Nodes in a WMN collaborate to provide end-to-end delivery by means of store-and-forward operations; a node can therefore act simultaneously as both client and router. WMNs present self-configuring capabilities, which makes their deployment extremely attractive from an economic point of view, avoiding the need for labor-intensive tasks (e.g., sending technician to install customer premises equipment) and allowing incremental deployment in an unplanned fashion (i.e., the larger the number of users, the larger the service coverage). With respect to conventional ad hoc networks [3], WMNs differ for (i) the goal, in that they are being intended as access architecture, not stand-alone systems (ii) the heterogeneity of the devices, in that there might be dedicated devices (with more powerful radio systems, multi-band capabilities etc.) acting as pure wireless routers. As an example, we may consider a wireless interconnection of hot spots, providing enhanced coverage without the need of having all of them wired to the Internet.

In order to be successful, WMNs must cope with current trends in services. It is indeed widely acknowledged that the next-generation Internet will be characterized by an extreme variety of multimedia broadband services. Without the ability to successfully support the peculiarities of these services, WMNs run the risk to remain a niche market. Unlike “pure data” applications like FTP or HTTP, next-
generation services are characterized by requirements in terms of network support, i.e., bandwidth, latency, packet delay jitter etc. On the other hand, these constraints fit badly the decentralized architecture of WMNs, where smart solutions are needed to provide such performance guarantees. It is therefore a primary need to perform performance measurements on real-world testbeds, in order to characterize the ability of WMNs to support multimedia flows and gain insight into the critical points of such systems, therefore providing smart guidelines for the design of innovative solutions able to boost WMNs deployment.

A small small-scale (7 nodes) IEEE 802.11-based testbed has been deployed at CREATE-NET premises. Such a testbed exploit the the Microsoft Mesh Connectivity Layer (see Sec. 6.2.2) in order to establish mesh connectivity. Performance measurements run over such a testbed has been exploited in order to evaluate the performance of current protocols in a wireless mesh environment using multimedia traffic patterns. The next steps will involve the design and realization of a wireless mesh testbed using 802.11 devices and exploiting Level 2.5 routing (see Sec. 2). The main expected result is the definition of a scalable architecture able to perform well in the presence of a large number of neighboring nodes. Particular emphasis will be devoted to multi-radio routing protocols. Novel results are expected in terms of algorithms, mechanisms and protocols for the support of Traffic Differentiation and Cooperation/Fairness Enforcement in WMNs. Proposed solutions will be implemented and validated through real-world experimentation carried over our testbed.

The remainder of this paper is organized as follows. In Sec. 2 we describe the mesh networking paradigm. Section 3 introduces our reference deployment scenarios. A survey of the state-of-the-art is the subject of Section 4. Section 5 illustrates the benefits that can be obtained by using a cross-layer approach. In Section 6 we give an overview of academic testbed and commercial solutions. Some interesting research direction are reported in Sec. 8. Section 7 describe the experimental settings and the traffic patterns used for the performance measurements and discusses the ability of current WMNs to support multimedia flows. Section 9 concludes the paper pointing out directions for future work.
2 Wireless Mesh Networks: Background, Motivations and Architecture

A WMN is a self-configuring network of nodes interconnected (possibly using multiple radio technologies/interfaces [4]) using wireless links. WMNs represent indeed the logical extension of WLANs, providing high-speed seamless connectivity to nomadic and mobile users. On the other hand, mesh networks inherit some features from the ad hoc networks field. In particular, WMNs use multihopping to transmit packets from the end user to the Internet gateway and vice versa, and are characterized by self-organization and self-healing capabilities, a key factor for enabling a rapid, effective and low-cost deployment. As highlighted in Section 1, WMNs differ from ad hoc networks for both the goal (WMNs are mostly intended as access networks to Internet gateways) and the devices heterogeneity.

Nodes in a WMN can play two different logical roles, i.e., mesh clients and mesh routers [1]. Mesh clients can be the source/destination of connections, while mesh routers are in charge of forwarding packets to and from the Internet. A single node can play both roles at the same time, as in standard ad hoc networking paradigms [3]. Multi-tier architectures can be envisaged [2], with mesh routers providing multihop backhaul connectivity to the Internet, while the clients act just as sources/destinations of Internet connections. Actually, these architectures provide more flexibility to system designers, in that powerful dedicated devices with specific features (e.g., multi-radio interfaces) can be used to perform packet forwarding, thus enhancing network performance. Mesh architectures can therefore be thought as a generalization of standard WLANs, where hotspots are wirelessly interconnected and multihop routing is exploited in order to extended both network coverage and reliability. The latter option applies usually to metropolitan-scale area networks, but we can also think of WMNs as extensions of standard indoor WLANs, where extended coverage can be obtained by allowing multihop communications by store-and-forward operations. It is worth stressing that, from our standpoint, WMNs are to be thought as access network architectures, and not as stand-alone “ad hoc” systems. Nonetheless, they share many features with conventional ad hoc networking paradigms. In particular, self-organization is expected to play a key role in mesh networking, for both client-to-router and router-to-router communications. The im-
The importance of self-configuring features comes from both (i) technical reasons, since it allows the deployment of unplanned networks while keeping at the same time backward compatibility with existing WLAN installations (ii) economical reasons, since it helps in lowering the entrance barrier to the ISP market, providing opportunities for SMEs to deploy backhaul networks in an incremental fashion.

Depending on the hierarchy introduced by the differentiation of nodes functionalities, WMN architectures can be classified according to the following taxonomy [1]:

- **Infrastructure/Backbone WMNs.** In infrastructure/backbone WMNs, as depicted in Fig. 1, wireless routers realize a self-configuring and self-healing mesh backbone, providing the clients with the opportunity to connect to a remote Internet gateway. Typical applications of this architecture are in community/neighborhood networking and in wireless mesh ISPs, where mesh routers are placed on the roof and a local in-home distribution service (either wired or wireless) is added to provide end-user connectivity. Examples of such architecture include the MIT’s Roofnet [5] and the (commercial) LocustWorld [6] deployments.

- **Client WMNs.** In client WMNs, sketched in Fig. 2, client nodes organize themselves into a flat architecture for providing Internet access by means of store-and-forward operations. This solution adapts well to extensions of indoor WLANs. On the other hand, it is not suitable for metropolitan-level networks due to the obvious scalability problems. The Microsoft’s Mesh Connectivity Layer [7] falls into this category.

- **Hybrid WMNs.** Hybrid WMNs represent the combination of the two aforementioned solutions, as depicted in Fig. 3. In this scenario a hierarchy, with dedicated mesh routers, is present, but at the same time client-to-client communications are enabled in order to extend the coverage and robustness of the single “cells”.

In principle, WMNs could interface, through suitable gateway nodes, networks based on different radio technologies (3G, WiFi, IEEE 802.15, WiMAX etc.). However, most actual solutions, in both the academic and the business environments, heavily rely on the IEEE 802.11 family of standards. This comes from both the
large availability of low-cost equipment on the market as well as from the “ad hoc” features already present in such family of protocols, which make it possible to obtain a mesh configuration with some rather minor modifications.
Besides, in terms of routing protocols, the most popular approach has been to re-use existing standards for ad hoc networks and adapt them to the peculiarities of the mesh environments [8]. The performance obtained by such systems are clearly far from optimal, and a lot of efforts are needed to enhance and optimize such solutions. In terms of protocol architectures, two solutions can be envisaged to forward and route packets on the mesh. In the first, the routing protocol is implemented directly at level three of the ISO/OSI stack, therefore (partially) modifying standard IP operations. In the second case, a 2.5-level routing protocol is provided, so that, to higher layer, the WMN appears like a LAN. The protocol stack of the two possible solutions is sketched in Fig. 4(a) and Fig. 4(b), respectively. The first choice provides more space for optimization and performance enhancements, but its implementation may not be trivial and may result platform-dependent. The second approach has the advantage of being transparent to standard networking stacks, so that it can be readily implemented over (virtually) any platform. On the other hand, it adds some overhead, thus lowering the network performance. Particular attention has been devoted to the introduction of novel routing metrics, able to attain better performance measures in outdoor scenarios and, in general, taking into account channel characteristics [8].
3 Application Scenarios

WMNs have been receiving considerable attention by the research community only for the last couple of years, boosted by their commercial deployment. At the moment there is a large number of companies active in this field, which provide solutions mostly based on the IEEE 802.11 family of standards [9]. At the same time, a large fraction of prominent universities and research centers are undertaking the deployment of experimental testbeds. Indeed, wireless mesh networking arise a number of challenges at various layers of the ISO/ODI stack. In this section, some reference application scenarios are introduced together with the research issues that need to be addressed in order to fully benefit of the mesh networking paradigm. Some promising research direction are highlighted.

3.1 Community Networks

With the term Community Networks we refer to a computer-based system developed with the intend to support geographical communities. Community networks exploit wireless LAN technologies to build clusters of linked, citywide networks. Such networks can be used share a cable or a DSL connection among several users using a wireless router. In this scenario an obvious problem is the location of the access points, which plays a key role in avoiding zones without service coverage. Moreover, communications between end nodes that belongs to different access points have to go all the way back to the access hub, introducing a single point of failure/congestion into the system.

WMNs mitigate the aforementioned shortcomings through flexible mesh connections between network nodes. In such a scenario, access points could be replaced by wireless mesh routers with mesh connectivity established among them. Therefore, the communication between those nodes becomes much more flexible and more robust to network congestion and link failures. WMNs can also enable many applications such as distributed file storage, and video streaming. Since wireless mesh routers have no constraints on power consumptions and mobility, protocols proposed for mobile ad hoc networks [3] and wireless sensor networks [10, 11] are too cumbersome to achieve satisfactory performance in this application.
Community mesh networks, and in general mobile ad hoc network, do not rely on an infrastructure, instead they are decentralized and self-organized. In order for the system to work, each node must accept to forward packets originated by other nodes. However, a node that is forwarding other nodes packets will consume own resources, in terms of energy & bandwidth. Albeit for individual nodes it is advantageous not to cooperate, for community multi-hop networks such a behavior leads to a degradation of the system performance. A similar fairness problem arise in peer-to-peer file sharing networks. As for example, BitTorrent [12] uses tit-for-tat as a method of seeking Pareto efficiency. Tit-for-tat is a strategy used in game theory [13]. An agent using this strategy will initially cooperate, then respond in kind to a previous opponent’s action. If the opponent previously was cooperative, the agent is cooperative. If not, the agent is not. This is equivalent to the concept of reciprocal altruism in the context of biology. Exploiting results achieved in game theory as cooperation/fairness enforcement mechanisms is an interesting research direction.

3.2 Metropolitan WISP Networks

Wireless Internet Service Provider (WISP) networks are intended to provide residential and business users with Internet access. WMNs are the ideal solution to provide broadband wireless connectivity in urban environments without the need for expensive wired network infrastructure. Moreover, the physical-layer transmission rate of a node in WMNs is much higher than any cellular networks. For example, a traditional IEEE 802.11g node can transmit up to 54 Mbps, while next-generation, 802.11n Wi-Fi standard will deliver up to 540 Mbps. A Wireless Metropolitan Area Network (WMAN) covers a potentially much larger area than home, enterprise, building, or community networks. Thus WMAN requirements on network scalability are stronger than that by other applications.

Traffic differentiation is a key requirement for metropolitan networks operated by WISP. In such a scenario the network operator is interested in providing qualitative and quantitative characteristics of the services provided to the customers in the

\footnote{A resource allocation for a given set of individuals is Pareto efficient, if no individual resource allocation can be made better without another being made worse.}
form of Service Level Agreement (SLA) tailored to specific customer’s classes (i.e. business and residential). Differentiated Services (DiffServ) [14] [15] and Virtual LANs (VLAN) [16] are two interesting approach for satisfying this traffic differentiation requirement. DiffServ is an architecture that attempts to provide service differentiation by using a class-based approach (as opposed to flow-based) where individual application flows with similar quality requirements are aggregated. A Per-Hop-Behavior is introduced in order to describe the treatment of aggregated traffic in a manner that ensures the quality guarantees provided by the corresponding service class. VLANs can be used in order to provide security by isolating traffic between different users. Moreover Different services can be tagged and mapped into different priority queues. Thus, Quality of Service can be achieved and improved. A suitable architecture for exploiting such approaches is an open issue.

In [17] an opportunistic scheduling algorithm exploiting the Hierarchical Token Bucket (HTB) paradigm is introduced. The algorithm is meant to be integrated in IEEE 802.11 Access Points and take into account both the service class required by the destination user and the channel quality experimented by the destination mobile STA (STA). Experimental results show that the proposed approach perform better than standard scheduling algorithms when radio channel quality is getting worse. More specifically the Wireless HTB does not penalize nodes that are experimenting good channel conditions. A similar approach can be exploited my mesh routers in order to obtain an increased aggregated throughput.

However, priority classes support at the MAC layer is mandatory in order to obtain real traffic differentiation. In this context, exploiting existing QoS-based IEEE 802.11e MAC protocol [18] is an interesting research direction (see Sec. 4.2).

4 State-of-the-Art

In this section an overview of the problems that have been analyzed in the literature is given in order to investigate how the mesh networking paradigm can be successfully applied to scenarios introduced in Section 3.
4.1 Physical Layer

Many approaches have been proposed to increase capacity and flexibility of wireless systems. Typical example includes directional and smart antennas, Multiple Input Multiple Output (MIMO) systems and multi-radio/multi-channel architecture. In [19] a number of enhancements exploiting beam forming antennas are evaluated using simulation. A capacity analysis for directional antennas is performed in [20]. In [21] a mechanically steerable antenna is proposed. Reconfigurable radio, frequency agile/cognitive radio and even Software Defined Radio have been proposed as techniques to improve both the performance and the manageability of radio subsystem by the upper layer protocols. A MAC protocol for Ad Hoc networks with MIMO links is presented in [22], where a centralized algorithm is introduced followed by its distributed approximation. The performance of the proposed approach are compared with some variants of the CSMA/CA protocol. The IEEE standard 802.11n [9] builds upon previous 802.11 standards by adding MIMO (Multiple-Input Multiple-Output). MIMO uses multiple transmitter and receiver antennas allowing increased range and data throughput. 802.11n devices are expected to deliver a nominal data rate up to 540 Mbps.

Research efforts required in order to fully benefits of these advances, are not limited to the physical layer but propagate to the upper layers of the architecture. Directional antennas, for example, reduce the exposed nodes; however at the same time they generate more hidden nodes. Such a behavior must be taken into account in designing an effective MAC layer for WMNs.

4.2 Medium Access Control

Scalability is a well know issue in multi-hop networking. When the size of the network increase the performance degrades significantly. Routing protocol may not be capable to find a route, transport protocol loose connection, and MAC protocols may experience throughput degradation. Due to the WMN’s distributed paradigm, implementing a TDMA or CDMA based MAC layer is not trivial. On the other hand, CSMA/CA based algorithms are easily deployable, but heavily limits the scalability of the networks. An hybrid approach exploiting both the CSMA/CA and the TDMA/CDMA techniques represents an open issue.
Scalability issue can be addressed allowing transmission on multiple channels in each transmission node. Such an approach heavily impact MAC design criteria. For devices with single transceivers only a channel at time can be used for transmitting, while multiple transceivers can exploit simultaneous transmission over different channels. Current IEEE 802.11 devices are equipped with a single half-duplex transceiver. The transceiver is capable of switching channels dynamically, but it can only transmit or listen on one channel at a time. Thus, when a host is listening on a particular channel, it cannot hear communication taking place on a different channel. In [23] a novel MAC protocol for multi-hop networks is proposed. This protocol exploit multiple channels dynamically in order to improve performance. The proposed approach enables hosts to utilize multiple channels by switching channels dynamically. The protocol requires only one transceiver per host, but solves the multi-channel hidden terminal problem using temporal synchronization. Simulations show that the protocol achieve higher throughput than IEEE 802.11. In [24] a distributed MAC protocol exploiting frequency diversity is presented. This protocol, called Slotted Seeded Channel Hopping (SSCH), is a virtual MAC protocol operating on top of standard IEEE 802.11 using a single transceiver. The SSCH layer in a node handles channel hopping by implementing the node’s channel hopping schedule and transmitting the channel hopping schedule to neighboring nodes. In a Multi-Radio scenarios a network node has multiple radios each whit its own MAC and physical layer. Since communications in these radios are totally independent, a virtual MAC protocol [25] is required on top of MAC to coordinate communications in all channels. In a Multi-Radio scenarios a network node has multiple radios each whit its own MAC and physical layer. Since communications in these radios are totally independent, a virtual MAC that coordinates multiple IEEE 802.11 radios operating over multiple channels is required. In [25] a new MAC layer protocol, called the Multi-radio Unification Protocol (MUP) is proposed. This protocol coordinates multiple IEEE 802.11 radios operating over multiple channels with the objective of exploiting the available spectrum more efficiently.

In order to provide differentiation mechanisms at MAC layer, a new protocol, IEEE 802.11e [18], has been developed by the 802.11 Working Group. The MAC protocol of 802.11e introduces two new access schemes: a distributed scheme called
Enhanced Distributed Channel Access (EDCA), and a centralized scheme called HCF Controlled Channel Access (HCCA). EDCA is a parameterized version of the previous distributed channel access mechanism of 802.11b that provide prioritized QoS by classifying traffic in Access Categories (ACs). Each AC has its own transmission queue and its own set of channel access parameters:

1. Arbitrary Interframe Space Number (AIFSN). The minimum time interval for the medium to remain idle before starting backoff.

2. Contention Window ($CW_{\text{min}}$ and $CW_{\text{max}}$). A random number is drawn from this interval for the backoff mechanism.

3. Transmission Opportunity (TXOP) limit. The maximum duration for which a node can transmit after obtaining access to the channel.

HCCA implements a polling scheme in order to allocate channel access to traffic flows based on their QoS requirements. As for 802.11’s Distributed Coordination Function (DCF), the EDCA is very likely to become the predominant access scheme for 802.11e networks. It is worth to note that those efforts address QoS requirements over a single hop, while per-flow (or per-class) differentiation over a WMN is an open research issue.

4.3 Network Layer

Multi-hop connectivity is a critical requirement for WMNs in order to extend network coverage and to provide NLOS connection. Multiple type of networks access, backbone and direct meshing among client nodes, must be provided. Moreover mesh routers internetworking with other wireless networks (e.g. WiMAX, ZigBee) is required. One of the objective to achieve in deploying WMNs is an increased robustness to link failure and network congestion. If a link breaks or experiences congestions the routing protocol should be able to select another path to avoid the broken/congested part of the network. Routing protocols for WMNs still require significant research efforts in the definition of new performance metrics exploiting cross-layer design principles. Existing protocols developed for ad hoc networking
need to be revisited or redesigned in order to take into account such approach. In [8], a detailed evaluation of the performance of different routing metrics is reported.

Routing protocol developed for ad hoc networks select path that minimize the hop count. However such a metric tend to use links between distant without taking into account packet loss or bandwidth. Indeed it has been shown [26] that minimizing the hop count does not lead to better performance. The Expected Transmission Count (ETX) [26] measure the loss rate of broadcast packets between pairs of nodes. However since broadcast packets are sent at the lowest speed (1Mbps for 802.11b/g, 6Mbps in case of 802.11a), they may not be representative for the loss rate experienced at higher data rate. Moreover the metric itself does not take into account link congestion and bitrate. Per-hop Round Trip Time (RTT) [25] measure the round trip delay between neighboring nodes using unicast probes. Such a metric is inertly load-dependent since it is affect by the queuing at each device. This queuing delay significantly distorts the RTT value on that hop. Moreover, this routing metric does not take into account link bitrate. Using large probes can help in estimating this parameters, however such a choice impact with the need of minimizing the metric overhead. Finally there are some scalability issue to since the metric require to probe each neighbor. Per-hop Packet Pair Delay (PktPair) measures the delay between a pair of probes of different size to a neighboring node. While this metric allows to obtain a better estimation of the channel bitrate and it is not affected by queuing delays at the sending node, since both packets in a pair will be delayed equally, it is also characterized by an higher overhead since two packet must be sent to each neighbor. Multi-radio routing is interesting paradigm since it allows to increase the capacity of the network without modifying the MAC layer. However, when nodes are equipped with multiple radio it is important to take into account channel diversity. In [4] a new performance metric for multi-radio WMN, called Weighted Cumulative Expected Transmission Time (WCETT), is proposed. Performance measurement run over a multi-radio testbed show that WCETT outperforms previously-proposed metrics.

The goal of a traditional routing protocol is to find the best sequence of hop between two nodes (according to a certain metric) and then route all packets using that sequence. Combining such an approach with a metric that prefer short
hops with an high delivery rate (like ETX [26]) does not take advantages of long but lossy links. In [27] ExOR a novel routing protocol is presented. ExOR takes advantages of long links by broadcasting each packet. The forwarder is chosen only after discovering the set of nodes that actually received that packet. Such an approach allows ExOR exploit long but lossy links that would have been ignored by traditional routing protocols.

4.4 Transport Layer

The performance of TCP are significantly affected by the peculiarities of multi-hop wireless networks. This is mainly linked with the incapacity of TCP to differentiate between congestion and non-congestion losses. As result when a packet is lost due to a medium error the throughput drops. Moreover when the channel condition are back to the normal TCP is unable to recover its performances quickly. This behavior is exacerbated by the asymmetric nature of the links in WMNs.

In such a scenario an interesting approach is designing a new transport protocol tailored for multi-hop wireless networks. However while this solution may be feasible for stand-alone ad hoc networks, it is not practical for WMNs since their nature of access network require a tight integration with other networking technologies. A promising approach to those issue is Performance Enhancement Proxies (PEP) [28]. PEP allows to split an end-to-end communication into several separate connections, enabling the use of a different transport protocol for each subnetwork.

In [29], APHON, a novel architecture for mitigating link-related performances degradation is introduced. APHON split end-to-end connection across different networks into two or more separate connection. Using this approach is possible to tune the performance of the protocol over single subnetwork rather then over the end-to-end path.

4.5 Application Layer

This section investigations about novel applications that need to be developed in order to fully take advantage of the WMN paradigm. While existing Internet applications must work out-of-the-box, a new generation of middleware tools need to be developed. Current managing functionalities are developed using a strongly centralized
approach. However the distributed and self-organizing nature of WMNs suggest a transition from network management (in terms of manual tweaking) to network monitor (in terms of fault detection and/or performance analysis). The advantages provided by such an approach are twofolds: (i) network operators can gain an increased insight into network behavior, usage and performance, and (ii) the research community is provided with precious guidelines for developing innovative solutions.

In [30] DAMON, a Distributed Architecture for Monitoring Mobile Networks, is introduced. Damon relies on agents within the network to actively monitor network behavior and send this information to data repositories. Damon’s generic architecture supports the monitoring of any protocol, device, or network parameter. The prototype presented in the paper is exploited for collecting statistics about data traffic and the AODV routing protocol.

5 Cross-layer Design

With respect to the scenarios introduced in Section 3, moving from a strictly layered protocol design in favor of a cross-layer architecture is a promising research direction for WMNs. While in the former approach each layer operates at a well defined level of abstraction and boundaries are chosen in order to minimize the information flow across the interfaces, in the latter approach, interaction between layers are taken into account and exploited in order to optimize the protocol efficiency. The system performance of future wireless multi-hop networks can then be greatly enhanced by a real merging of functionalities between PHY, MAC and higher layer protocols. As shown in [31], multiuser diversity can substantially improve wireless network throughput. In such an approach each user reports to the base station its “instantaneous” channel capacity. This information can be exploited by the scheduling algorithm in order to take advantage of channel variations by giving priority to users with instantaneously better channels.

It is worth noting that a layered architecture enables protocols designers to concentrate their efforts at a particular level without worrying about the rest of the protocol stack. However, once the layering is broken such an approach is no more viable, and the effects of any single design choice on the whole system needs to be considered. In [32] it is shown that that unintended cross layer interactions
can have undesirable consequences on overall system performance and a few general principles for cross-layer design are given.

In MobileMAN [33], information collected at different layers of the networking stack are shared in a common local memory structure and exploited to adapt the behavior of the node depending on the particular circumstance the node operates in. Such an approach satisfies the layer separation principle, i.e., protocols belonging to different layers can be added/removed from the protocol stack without modifying the protocols operating at the other layers. All protocols can access this common memory structure for writing information to share with the other protocols, and to access information published from the other protocols. This has several advantages:

- It is full compatible with standards, since it does not change the core functionalities of each layer.
- It maintains a transparent architecture, since protocols belonging to different layers can be added/removed from the protocol stack without modifying the operations at the other layers.
- It maintains all the advantages of a modular architecture.

6 WMNs Deployments

The growing interest in WMN has driven industrial efforts to develop proprietary solutions for both indoor and outdoor environments (e.g., Tropos, BelAir, Firetide, LocustWorld, MeshNetwork and Strix). These solutions adopt radically different approaches and protocols, making these systems incompatible. On the other hand, there are significant efforts from nonprofit and research institutions in order to implement real world prototypes and testbeds based on non-proprietary off-the-shelf technologies.

As stated previously each mesh node must be completely self-configuring. In order to achieve this goal the software must automatically solve a number of problems: allocating addresses, finding a gateway between the mesh node and the Internet (the default gateway), and choosing a good multi-hop route to that gateway. In this section the design choices of some of these experimental testbeds are briefly sketched.
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6.1 Academic testbeds

6.1.1 Roofnet

Roofnet [34] is an experimental multihop 802.11b-based mesh network consisting of about 50 nodes located in Cambridge, Massachusetts, installed and operated by the Massachusetts Institute of Technology (MIT). The network participants are volunteers who accept hosting in their apartments the equipment required to implement a mesh node. Each node is equipped with a single 802.11b wireless card with RTS/CTS disabled. All cards share the same 802.11b channel. Multi-hop routing is implemented using the MIT’s modular router Click [35]. Each node also runs a Web server, a NAT, and a DHCP server on its wired Ethernet port.

Roofnet routes packets using SrcRR a protocol inspired by DSR [36]. The original protocol has been modified extensively, mainly for supporting link-quality metrics. SrcRR uses the ETX [26] for choosing good routes. ETX (Estimated Transmission Count) continuously measures the loss rate in both directions between each node and its neighbors using periodic broadcasts. The metric assigned to each link tries to estimate the number of times a packet have to be transmitted before both the packet and the corresponding ACK are received successfully SrcRR is independent from IP, and operates at a lower layer using it own frame format.

From the user’s perspective, the node acts like a cable or DSL modem: the user connects a PC or laptop to the node’s Ethernet interface, and the node automatically configures the user’s computer via DHCP, listing the node itself as the default IP router. Users can choose to connect the node to a wireless access point. Roofnet carries IP packets inside its own frames. Each Roofnet node needs a unique address at the Roofnet layer, as well as an IP address. The Roofnet software running on a node must be able to assign itself addresses automatically, without requiring explicit configuration. This is done by choosing an address whose low 24 bits are the low 24 bits of the node’s Ethernet address, and whose high 8 bits are an unused class-A IP address block (10.x.x.x). The node uses the same address at both the Roofnet and IP layers. These addresses are meaningful only inside Roofnet and they are not globally routable.
6.1.2  BWN

The testbed developed at the Broadband and Wireless Network (BWN) [37] Lab at Georgia Institute of Technology is made of 15 IEEE 802.11-based mesh routers (laptops and desktops). Some of those nodes act also as gateway providing internet connectivity the the WMN using the next generation Internet testbed (also available in the BWN Lab). The mesh testbed is integrated with the already existing BWN Sensor Network Testbed in order to evaluate feasibility of protocols applicable to heterogeneous wireless networks.

6.1.3  Hyacinth

Hyacinth [38] is a multi-channel WMN built using IEEE 802.11 a/b/g technology. The Hyacinth prototype currently has 10 nodes that are built using small form-factor PCs each equipped with three 802.11a NICs. In order to have two nodes communicate with each other, their interfaces must be tuned to the same channel. However, increasing the number of interface on the same channel leads to an increased interference and then to a lower bandwidth. A novel channel assignment algorithm [39] has then been developed in order to find a balance between maintaining network connectivity and increasing the aggregate bandwidth.

6.1.4  UCSB

The UCSB Mesh Testbed [40] is an experimental wireless mesh network deployed on the campus of UC Santa Barbara. The network consists of 25 nodes equipped with multiple IEEE 802.11a/b/g wireless radios distributed over a five floors campus building.

Each node is composed by two Linksys WRT54G wireless devices. One devices act as mesh router running the AODV [41] routing protocol. The second device is used for out-of-band management of the AODV mesh node. Gateways are deployed using a small form-factor PC running Linux. Each gateway is equipped with a 802.11b radio and an Ethernet interface. The wired interface is used to provide Internet access to the mesh devices while the wireless interface is used for meshing with the other nodes.
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6.1.5 CUWiN

The Champaign-Urbana Community Wireless Network (CUWiN) project [42], a non-profit organization supported by grants and donations, wants to build and implement a mesh-style Community Wireless Network that allows anyone within range of the Network to get on-line, free from monthly fees, using off-the-shelf wireless hardware. CUWiN is designing a system to prioritize routes among mesh nodes based on MIT Roofnet, and are looking into the Hazy Sighted Link State (HSLS) routing issue. HSLS is a Link-state routing protocol that uses packet economics: more dropped packets in a given route de-emphasizes it shunting more traffic to more successful routes.

CUWiN has been developing an open-source (under the GPL license), turnkey wireless networking solution that exceeds the functionality of many proprietary systems. To set up a network, all end-users need to do is burn a CD with CUWiNs software (which will be available for free at www.cuwireless.net), put the CD into an old desktop computer equipped with a supported wireless card, and turn the computer on. Once the computer boots from the CD, the rest of the setup is completely automated: from loading the networking operating system and software, sending out beacons to nearby nodes, negotiating network connectivity, and assimilating into the network all the complicated technical setup is taken care of automatically. Unlike most broadband systems, CUWiNs software builds a local intranet as well as providing for Internet-connectivity. Thus, a town that uses CUWiNs system is also creating a community-wide local area network over which streaming audio and video, voice services, etc. can all be sent.

6.2 Commercial solutions

6.2.1 LocustWorld

A special case is the LocustWorld [6] company that produces mesh routers, called MeshBoxes, based on open source software components. The MeshBox provides a WiFi access point and onward routing to other MeshBox devices. Multiple MeshBoxes within range of each other intercommunicate to provide a self organizing network, with dynamic routing between nodes. WiFi users connected to one mesh
node can then obtain network services from other mesh nodes, such as broadband Internet. Each node consists of a PC, an 802.11b card, and an omni-directional antenna. The MeshBox runs a customized Linux kernel, with mesh routing (AODV is used as layer-3 routing protocol [41]) and interactive functions provided as Linux applications. Each node allocates itself an address, typically in the 10.x.x.x range on the wireless interface and attempts to find an Internet gateway using a DHCP client on the Ethernet interface. If no gateway can be found, the software considers that it has only wireless links and configure itself as repeater-cell.

6.2.2 Microsoft Mesh Connectivity Layer

The Mesh Connectivity Layer (MCL) [7] is a loadable Microsoft Windows driver. It implements an interposition layer between layer 2 (the link layer) and layer 3 (the network layer) of the standard ISO/OSI model. It is sometimes referred to as layer 2.5. To the higher layers, MCL appears to be just another Ethernet link, albeit a virtual one. To the lower layers, MCL appears to be just another protocol running over the physical link. MCL routes using a modified version of DSR [36] called Link Quality Source Routing (LQSR) [4]. LQSR assigns a weight to each link. This weight is the expected amount of time it would take to successfully transmit a packet of some fixed size on that link. In addition, the channel, the bandwidth, and the loss rate are determined for every possible link. This information is sent to all the nodes. Based on this information, LQSR uses a routing metric called Weighted Cumulative Expected Transmission Time (WCETT) [8] to define the best path for the transmission of data from a given source to a given destination.

6.2.3 Firetide

Launched in 2003, Firetide Inc. [43] is a privately held wireless mesh technology company that develops networking equipment to deploy high performance mesh networks quickly, easily and affordable. Firetide’s mesh networking solution is ideal for building backbone infrastructure for Wi-Fi networks, video surveillance, and temporary networks in a variety of environments, such as metro-area Internet access HotZones, airports, hotels, campus environments or other locations where wiring is difficult, disruptive, or expensive.
FireTide’s broadband radio mesh HotPoint Network is an IP network supporting multi-hop, point-to-point and multi-cast routing. HotPoint routers use a FireTide-enhanced version of the Topology Broadcast based on Reverse-Path Forwarding (TBRPF) routing protocol to manage the unique and dynamic environment of the mesh network. A patented technology allows the HotPoint routers to find each other automatically and form a mesh network. Adding HotPoint mesh routers to the network is as simple as plugging them into an AC power source. Multi-hop routing allows the network to extend to any distance. You can add, remove, or relocate HotPoint routers whenever you wish without disrupting the rest of the network or rebooting the system. If a HotPoint router is moved to a different location or is removed completely, the network will automatically heal itself and reroute packets accordingly.

6.2.4 MeshNetworks

MeshNetworks had been acquired by Motorola [44] on November 2004. The main application of Motorola technology is to provide mobile broadband internet access by means of supporting high speed mobile users throughout the use of QDMA (quad-division multiple access) protocol, a proprietary radio technology developed for and currently used by the military. Another important feature of Motorola mesh networking technologies is the building of its proprietary MeshNetworks Scalable Routing (MSR) protocol. MSR technology utilizes an optimized and proven hybrid ad hoc routing algorithm that combines both proactive and reactive routing techniques. This enables support for high speed mobility, unmatched scalability and low messaging overhead.

6.2.5 Tropos

Tropos Networks MetroMesh architecture [45] includes the Tropos MetroMesh OS with Predictive Wireless Routing Protocol (PWRP) and purpose-built outdoor, mobile and indoor MetroMesh routers operating at 2.4 GHz. At the core of the MetroMesh OS is the PWRP. This intelligent routing protocol negates effects of radio frequency interference, wired backhaul failure and mesh router failure. It scales to thousands of nodes with the lowest routing overhead in the industry, not exceed-
ing 5% of available bandwidth regardless of network size, and is the industry’s only purpose-built mesh routing protocol built on the important principal of optimizing client-server throughput.

6.2.6 BelAir Networks

BelAir Networks wireless mesh solutions [46] are characterized by a multi-interface approach. Each node supports three radios that are dynamically mapped on any one of the eight backhaul antennas with no need for manual pointing. The selection is done under software control via BelAir Networks patent pending autoantenna selection algorithm. The BelAir technology supports features like load balancing to reduce the impact of link congestion and failure and to increase system up-time and minimize traffic outages. Furthermore, a BelAir wireless mesh node implements radio-aware routing algorithms that choose the best route for traffic based on available capacity, latency and PHY feedback.

6.2.7 MeshDynamics

MeshDynamics [47] provide multi-interface mesh solutions based on 802.11 devices. This architecture provides separate backhaul and service functionalities and dynamically manages channels of all of the radios so that all radios are on non-interfering channels. In the 3-radio configuration, 2 radios provide up link and down link backhaul functionality, and the other radio provides service to clients.

7 Performance Evaluation

In this section, we report some performance measurements obtained at our CREATE-NET testbed on a small-scale (7 nodes) IEEE 802.11-based WMN. The tests aim at characterizing the ability of current WMN technology to support multimedia flows. The literature provides already some performance studies on WMN testbeds, from which our work differs in (i) the network architecture, in that we employ a single-tier architecture and (ii) the evaluation methodology, in that the performance of a mesh architecture is compared to that obtained by a standard star-shaped single-hop architecture.
Most works in the literature focus on outdoor metropolitan-scale deployments. For instance, [48] reports an analysis of the possible sources of packet loss in an outdoor WMN, assessing the effect of link distance and signal-to-noise ratio on the link quality statistics. Results show that a sharp dichotomy between working and not working link cannot be found, the majority of the links being characterized by an intermediate loss rate. In [34], the performance of an outdoor WMN is evaluated, discussing the effect of node density on network connectivity and throughput. Compared with a star-shaped network, the mesh architecture improve both the connectivity and the throughput. Results for an indoor environment are reported in [49], where the performance of multimedia flows over an IEEE 802.11-based two-tier WMN are given in terms of packet latency, loss rate, inter-flow fairness and jitter for different network configurations. Results show that the number of multimedia flows that can be supported by the network is constrained by the application packet rate and not by the data rate or by the packet size. The impact of Request To Send/Clear To Send (RTS/CTS) is analyzed by comparing the number of video flows supported by the network with RTS/CTS and without. RTS/CTS turn out to limit the performance of the network in terms of number of concurrent video flows. An indoor scenario is considered in [4], where a routing metric exploiting multiple radio devices is shown to achieve higher throughput than other metrics (such as those based on the shortest path algorithm).

### 7.1 Network configuration

The experimental data has been collected exploiting a 7-nodes wireless testbed deployed in a typical office environment implementing a single-tier structure, as sketched in Fig. 5. Testbed’s nodes are all Dell notebook model D600/D610/D810 equipped with a 1.86GHz Intel Pentium M processor with 512MB of memory. All nodes run Microsoft Windows XP Professional. Each node has a single Intel 2915ABG or a Dell 1470 Wireless adapter with RTC/CTS disabled. For the infrastructure test we used a Cisco Aironet 1200 Access Point (AP) [50] that supports both 802.11a and 802.11b/g operation mode. The AP is equipped with 2 omni-directional antennas with a gain of 2.14 dB. The default maximum output power of the access point is 50 mW. However, we decided to reduce this value to 20mW.
(which is the maximum output power of our wireless adapters) in order to have the same operating conditions for both the infrastructured and the mesh modes.

During our measurements, functionalities provided by node number one are twofold. In the mesh scenario, it acts as gateway to the Internet, with the routing protocol running on it. In the infrastructured scenario, it is attached through an Ethernet connection to the AP. All measurement are run using IPv4 with statically assigned addresses and IEEE 802.11 operating in “g” mode. In order to increase the reliability of our results, we have exploited the AP’s site survey tool in order to detect the presence of interference caused by other 802.11 devices. The operating channel for both the AP and mesh scenarios has been chosen according to this analysis. Mesh connectivity is realized using the Microsoft Mesh Connectivity Layer [7] as described in Sec. 6.2.2.

Figure 5: Testbed planimetry. Node number 1 provides a twofold functionality. In the mesh scenario, it acts as gateway, while in the infrastructured scenario it is attached through an Ethernet connection to the AP.
7. PERFORMANCE EVALUATION

7.2 Multimedia Traffic Patterns

The experimentation has been performed using synthetic traffic generated by means of the Distributed Internet Traffic Generator (D-ITG), a freely available software tool [51]. D-ITG can generate and inject different traffic patterns over TCP and/or UDP sockets. The traffic is then collected at the receiver side where suitable tools can provide a great variety of statistical analysis. By means of D-ITG it is possible to simulate many traffic scenarios originated by a large number of users and network devices, whereas other traffic generators have limited capabilities in terms of performance and range of source models.

Looking at multimedia communications, we focused on a video conference application due to: (i) its widespread use (e.g. Skype 2.0) and (ii) its strong requirements in terms of Quality-of-Service. Actually, we chose such a real-time service since it is one of the most demanding in terms of loss and delay constraints. Therefore, it is particularly suited to stress the network, especially when dealing with mesh structures, where multihop communication could introduce unacceptable delays.

<table>
<thead>
<tr>
<th>Rate (Packets/sec)</th>
<th>Video (H.264)</th>
<th>Audio (G.729.3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload length (Bytes)</td>
<td>800</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 1: Flows characterizing the video conference traffic pattern (UDP)

We have emulated each video conference service by continuously transmitting two UDP packet flows at the same time: a voice stream and a video stream. For the former one, we have considered the G.729.3 codec [52], a worldwide used speech codec for VoIP applications, with each packet containing three voice samples and without Voice Activity Detection. The video stream has been generated according to the recently approved H.264 standard [53], well-known for its compression performance. We assumed that a good video quality can be attained by coding the video using 10 frames/sec [54], in such a way that one frame can be carried in one packet. The properties of both flows are summarized in Table 1. As it can be read from Table 1, each video conference application requires 75 kbit/sec including RTP headers. On the other hand, best effort traffic (in our case persistent TCP connections) is modeled considering a TCP socket working in saturation regime, according
<table>
<thead>
<tr>
<th></th>
<th>Best Effort (FTP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate (Packets/sec)</td>
<td>2000</td>
</tr>
<tr>
<td>Payload length (Bytes)</td>
<td>1240</td>
</tr>
</tbody>
</table>

Table 2: Flow characterizing the best-effort traffic pattern (TCP)

to the parameters reported in Table 2. In order to collect reliable measure of delays, before each experiment we synchronized each node with a common reference using NTP [55].

### 7.3 Performance Measurements

In this section we report the outcomes of some experimental tests run with the equipment and settings described in Sec. 7.1. As said before we compare the results obtained exploiting our mesh architecture, with the ones achieved using the infrastructured scenario. Due to the preliminary nature of this work, the tests reported refer to downlink traffic only. The nodes are activated according to the numbering in Fig. 5, so that when $N$ flows are active hosts 2, 3, …, $N + 1$ are downloading from host 1.

As outlined in Sec. 7.2 two traffic patterns are considered. First, we will focus on data traffic only, where persistent TCP connections are emulated. In this case, we will consider the average throughput experienced by each node. We will consider as performance metrics both the mean aggregated throughput (which, roughly speaking, shows the ability of the system to efficiently use the available bandwidth) and the fairness, defined according to the classical Jain’s index [56]:

$$f = \frac{(\sum_{i=1}^{N} x_i)^2}{N \sum_{i=1}^{N} x_i^2},$$

where $x_i$ denotes the average throughput experienced by node $(i + 1)$. The fairness index $f$ is an indicator of how fairly the overall bandwidth is shared among competing connections. In the infrastructured mode, this depends mainly on the different channel conditions encountered on the links, exacerbated by the dynamics of TCP’s congestion control mechanism, which has the overall effect of penalizing the hosts far away from the AP. On one hand we can expect the mesh architecture
Figure 6: TCP average throughput versus number of concurrent flows using the two different network architectures.

to provide a higher level of fairness, in that hosts far away from the AP could exploit relays to enhance their throughput. On the other hand, in the mesh case, links may be shared by multiple connections, giving rise to problems of buffer overflows with possibly negative effects on the overall performance.

The results for the aggregated throughput and the fairness index are plotted in Fig. 6 and Fig. 7, respectively. The infrastructured mode provides better performance in terms of aggregated throughput. However, the higher bandwidth utilization is achieved at the expenses of nodes with poor channel conditions. This is shown in Fig. 7, where mesh architecture performs slightly better than infrastructure mode in terms of fairness. In Table 3, we reported the average throughput experienced by each node for the case of six best-effort flows. There is a higher variance for the AP with respect to the mesh architecture, thus confirming the results in terms of fairness.

The other tests refer to video conference applications, modeled according to the parameters detailed in Sec. 7.2. In this case we look at packet delays and losses as the two main QoS metrics. We expect the mean packet delay to be higher in the case of mesh architecture, due to the processing and buffering at each node necessary to
Figure 7: TCP fairness versus number of concurrent flows using the two different network architectures.

<table>
<thead>
<tr>
<th>Node Id</th>
<th>Infrastructured Average bitrate (kbit/s)</th>
<th>Mesh Average bitrate (kbit/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1967</td>
<td>783</td>
</tr>
<tr>
<td>3</td>
<td>1657</td>
<td>680</td>
</tr>
<tr>
<td>4</td>
<td>1062</td>
<td>1065</td>
</tr>
<tr>
<td>5</td>
<td>2018</td>
<td>605</td>
</tr>
<tr>
<td>6</td>
<td>1355</td>
<td>640</td>
</tr>
<tr>
<td>7</td>
<td>1966</td>
<td>773</td>
</tr>
</tbody>
</table>

Table 3: Average throughput for six best-effort flows using the two different network architectures

perform store-and-forward operations. This is confirmed from the results plotted in Fig. 8, which reports the average delay vs. number of concurrent multimedia flows. On the other hand, the effect of such operations on the detailed statistics, i.e., Probability Distribution Function (PDF), is hardly predictable. Indeed, on one hand we expect the buffers at intermediate nodes to act as “integrators”, smoothing the delay PDF. On the other hand, the buffering could introduce unpredictable delays, worsening the overall performance. The results are reported, in terms of delay PDF in Fig. 9. As it may be seen, the mesh architecture presents a smoother
delay PDF. This is generally acknowledged to have a beneficial effect on multimedia flows, in that it facilitates the design and dimensioning of playout buffers. In Table 4 we reported the sample mean and sample standard deviation for the packet delay, for both infrastructured and mesh mode, in the case of six concurrent multimedia flows. Finally, Fig. 10 reports the mean packet loss rate for both considered architecture. It can be seen that the mesh architecture presents a lower packet loss rate than the infrastructured architecture when the number of concurrent multimedia flow is rather large. This suggests that the mesh architecture presents better scalability properties than conventional access-points based WLANs.

8 Research Direction

Most of the research efforts done for ad hoc networks was dedicated to realize military application or very specialized civil application (disaster recovery, planet monitoring). On the other hand potential WMN users are much more interested in broadband access to the Internet. In such a scenario it is essential that all user can achieve a fair use of the available resources. Unfortunally current networking
Figure 9: Packet Delays’s Probability for six concurrent Multimedia Flows using the two different network architectures.

Table 4: Average delays for six multimedia flows using the two different network architectures.

In this research we aim at developing novel algorithms and protocols for enabling WMNs as the standard access architecture for next generation ubiquitous Internet access. Indeed, while some early experimental deployments of WMNs are already up and running, proving the validity and feasibility of the underlying architectural concepts, they rely on technologies and solutions (IEEE 802.11 MAC, ad hoc routing protocol are unable to satisfy such a requirement leading to severe unfairness to user located far from the mesh border gateway.
Figure 10: Packet loss versus number of concurrent flows using the two different network architectures.

protocols) that were designed for a different application scenario [2]. This leads to suboptimal performance, far from those required to provide truly broadband Internet access to end users. Our research will then exploit the peculiarities of WMNs to overcome the limits of the current proposed solutions in a next-generation Internet perspective. Design and implementation of a wireless mesh testbed based on off-the-shelf technology is an expected result for this research.

A comprehensive set of measurements run over an 802.11-based wireless mesh testbed will be exploited in order to evaluate the performance of current protocols over WMNs, providing precious guidelines for the design of innovative solutions. Building on these results, we will characterize mesh-based networks in terms of efficiency, robustness and reliability, and we will compare them with more conventional architectures. The main expected results is the definition of a scalable architecture able to perform well in the presence of a large number of neighboring nodes. Particular emphasis will be devoted to multi-radio routing protocols. Proposed solutions will be implemented and validated exploiting a wireless mesh testbed based on off-the-shelf technology. Novel results are expected in terms of algorithms, mechanisms and protocols for the support of Traffic Differentiation in WMNs. Such a feature is
particularly relevant in metropolitan scale networks operated by a WISP. In such a scenario it is required to define the qualitative and quantitative characteristics for the services provided to the customers in the form of SLAs. A decentralized and self-organized reputation system is required in order to provide incentives for cooperation and to protect community networks from node misbehavior. In this scenario, no “a priori” trust exists among the involved parties (the nodes participating the community). Then, trust must be built from scratch without relying on a specific infrastructure.

9 Conclusions

The mesh architectures may represent a feasible solution for providing broadband multimedia services in community and metropolitan wireless networks without the need for deploying a fixed infrastructure.

The results presented in this report are a first step toward the understanding of the real capabilities of mesh-based architectures. In particular, mesh architectures have shown to be able to attain a better fairness in bandwidth sharing with respect to conventional star-like topologies. Further, the effect of buffering at intermediate nodes is to smooth the packet delay PDF, with a beneficial impact on the performance of jitter-sensitive multimedia flows. It is worth recalling that our measurements were based on standard off-the-shelves devices and a freely available software package for mesh networking. We believe that the performance measures we obtained could be highly improved by optimizing the protocols for the application scenarios we considered.

Our future plans include the extension of the testbed size (in terms of number of connected devices and network coverage) to study the scalability of mesh architectures and the optimization of the protocol stack for enhancing system performance.

References

REFERENCES


