Multimedia over Wireless Mesh Networks: Results from a Real Testbed Evaluation

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Abstract— **Wireless mesh networks are the next step in the evolution of wireless architecture, delivering services for a large variety of applications in personal, local, campus, and metropolitan areas. Unlike WLANs, mesh networks are self-configuring systems where each Access Point (AP) can relay messages on behalf of others, thus increasing the range and the available bandwidth. Key advantages of wireless mesh networks include ease of installation, no cable cost, automatic connection among nodes, network flexibility, discovery of newly added nodes, redundancy, and self-healing reliability. At UCLA Network Research Lab, we created a testbed for Wireless Mesh Networks using the Mesh Connectivity Layer, part of the Microsoft Mesh Toolkit 2005. In this paper we focus on indoor scenarios, such as home environments and offices. As the demand for rich-media, streaming video content continues to increase, this kind of applications certainly represents a main player in the considered scenarios. Using our testbed, we delineate the limits of multimedia streaming with today's WMN technology.**

I. INTRODUCTION

Wireless Mesh Network (WMN) technology has been gaining visibility and importance in distributed applications that cannot rely on a fixed infrastructure but require instant deployment, dynamism, self-organization and self-configuration. A WMN is an IEEE 802.11-based hybrid network of wireless nodes and can be considered a variant of a Mobile Ad-hoc Network (MANET). Its nodes can be classified in four different categories (see Figure 1):

- Mesh Point (MP) provides mesh services. It can be a dedicated infrastructure device or a regular user device enabled to fully participate in the network, i.e., it can relay messages in ad-hoc fashion on behalf of other MPs to create a self-configuring system that extends the coverage range and increases the available bandwidth.
- Mesh Portal Point (MPP) is a MP that also provide direct access to wired connectivity. It supports transparent bridging, address learning, and bridge-to-bridge communication.
- Mesh Access Point (MAP) embodies a special type of MP which provides AP services in addition to mesh services provided by MPs.
- Station (STA) is a totally mobile user device and does not participate in mesh services. Two STAs can communicate only through an AP.

The novelty of WMN is that, if the source and the destination stations are not in the same Basic Service Set (BSS) domain, the source MAP does not forward the packet to all the MAPs in the Extended Service Set (ESS) but the packet is sent along a MPs path to reach the destination station [1]. We can view a mesh network as a multi-hop ad-hoc, packet switching and forwarding network between MPs in the same ESS. The

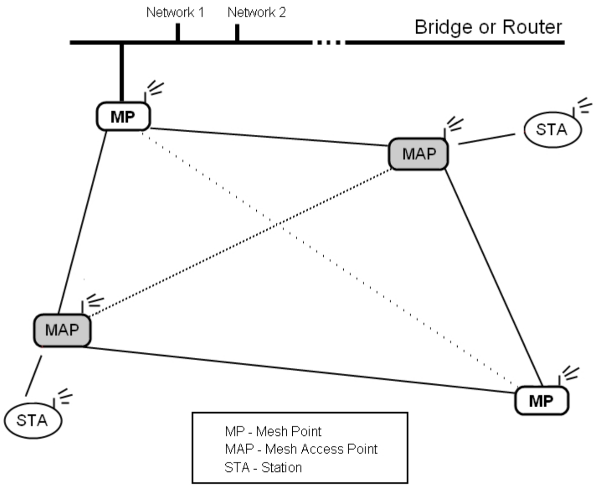

Fig. 1. Wireless Mesh Network

Wireless Distribution System (WDS) uses an extension of the IEEE 802.11 MAC/PHY, named IEEE 802.11s, to provide a protocol for autoconfiguring paths between MPs in a multi-hop topology, supporting broadcast, multicast and unicast traffic.

WMN can be put to good use in several scenarios; one of the most important, is the digital home. In this case, the primary purpose of the WMN is to create a low-cost, easily deployable, high performance wireless coverage throughout the home, eliminating radio frequency (RF) dead-spots. Another useful application of WMN is in an office where Ethernet cabling does not exist or its installation is economically prohibitive. With WMNs, enterprises can reduce the cost and the time associated with cable installation. Examples include small and large offices, manufacturing plants, university campus, government buildings, and health care/hospitals.

The aim of WMN technology is to provide capabilities that can facilitate the deployment of multi-hop wireless networks with access to the Internet. Indeed, WMNs enable Internet access services with higher reliability thanks to a fault tolerant infrastructure and redundant access links. Here, we evaluated the performances achieved by a real WMN, with an increasing number of connection hops, supporting multimedia traffic in an indoor environment.

The main contribution of this paper is hence twofold: i) reporting on the deployment of a real indoor testbed utilizing state-of-art WMN technology and ii) evaluating the factual capability of this technology in supporting one of the most demanding, yet more and more popular, kind of application, i.e., rich-media streaming.

The rest of the paper is organized in the following way. In Section II, we review WMN state of art. Section III describes WMN and the software used to build the testbed. Intensive performance evaluations for wireless mesh networks are presented in Section V. Finally, conclusions and future works are reported in Section VI.

II. BACKGROUND

WMNs are composed of Mesh Points (MPs) that facilitates the connectivity and intercommunication of wireless clients through multi-hop wireless paths, as described before. Moreover, WMN may be connected to the Internet trough gateways named Mesh Portal Points (MPPs). Therefore, in a WMN, the MPs embody the routing nodes. Therefore, unlike legacy ad-hoc networks (e.g., MANETs), in WMN end hosts and routing nodes are distinct.

Another big difference between WMNs and ad-hoc wireless networks is that the MPs in WMNs are usually stationary and typically not power-constrained. Therefore the routing protocols do not have to deal with mobility to find high throughput routes; neither has to consider node energy level to avoid network partitioning.

In this paper we are focusing on indoor environment scenarios (e.g., home, office). Needless to say, an important role in this context is played by multimedia traffic, which also represents one of the most resource consuming transmissions. Companies from all business sectors are discovering the marketing power of streaming video communication that reaches thousands of viewers at their home or work. Indeed, the demand for rich-media, streaming video content continues to increase. WMN promises to be an easy deployable infrastructure that can support multimedia content deliver. Using the NRL-WMN testbed, we delineate the limits of a real WMN that uses today's technology.

To the best of our knowledge, even if many research groups are starting to build WMN testbeds [2] [4] [5] [6], no one has yet evaluated the performance of real-time traffic in a WMN.

The Broadband and Wireless Network (BWN) Lab at Georgia Institute of Technology [2] has recently built a WMN testbed. This WMN, called BWN-Mesh, consists of 15 IEEE 802.11b/g based mesh routers, with several among them connected to the Internet. The routers are located in various rooms on the floor where the BWN Lab resides. By changing the topology of the network, experiments investigating the effects of inter-router distance, backhaul placement, and clustering were performed along with mobility experiments using laptops in the testbed. Moreover, existing protocols (i.e., TCP, AODV, and IEEE 802.11g [3] as transport, routing, and MAC protocols, respectively) for BWN-Mesh testbed have been evaluated, demonstrating that they do not perform well in terms of end-to-end delay and throughput in WMNs. Currently, the research is focused on adaptive protocols for transport layer, routing and MAC layers, and their cross-layer design.

The University of California, Santa Barbara Mesh Testbed [4] 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 and distributed on five floors of the Engineering 1 building. The focus is that of designing protocols and systems for the robust operation of multi-hop wireless networks.

MAP at Purdue [5] is an experimental wireless mesh network testbed at Purdue University that currently consists of 32 nodes (laptops and PDAs) and is capable of running in both 802.11a and 802.11b/g mode. The testbed has been recently enhanced with multi-radio support for higher capacity to develop and test WMN as Internet access. Furthermore, MAP includes also a mobile ad-hoc network testbed consisting of 5 laptops and 16 Compaq IPAQ PDAs.

A WMN testbed using Intel IXP425 series XScale network processors as routers and iPAQ as clients has been built at Carleton University [6]. Two Wireless LAN network interfaces are installed on the two Mini-PCI slots, one is Prism 2 / 2.5 card, which supports IEEE 802.11b, and another is Atheros card, which supports IEEE 802.11 a/b/g.

III. WIRELESS MESH NETWORKING THROUGH MCL

Microsoft Mesh Connectivity Layer [7] is a Microsoft Research open source WMN implementation. It is a virtual adapter that Windows applications can use just like any other network connection. It comes with a configuration and diagnostic utility, as well as a link statistics analyzer called TTCP.

Architecturally, MCL fits between the network and link layers, providing an abstraction level to its surrounding layers and minimizing the changes required to make them work with it. The existence of this 2.5 interlayer protocol is transparent to protocols running on top of it (e.g., TCP/IP), as well as those running beneath it (e.g., MAC layer). There is hence no need to change these technologies in order to work with MCL.

As its routing protocol, MCL uses a modified version of Dynamic Source Routing [8], called Link Quality Source Routing (LQSR) that identifies all the MPs in a WMN and assigns relative weights to the links among the nodes. More in detail, information such as the channel, the bandwidth, and the loss are determined for every possible link and sent to all nodes. Exploiting this information, LQSR defines the best path for the data transmission from a given source to a given destination. The utilized routing metric is known as Weighted Cumulative Expected Transmission Time (WCETT) [9]. If the optimum path between a particular source and the corresponding destination changes, LQSR modifies the route accordingly, without interrupting the link between the nodes.

Hybrid Wireless Mesh Protocol (HWMP) is the default routing protocol of IEEE 802.11s. It combines a reactive (Ad-hoc On demand Distance Vector - AODV [10]) and proactive tree-based routing protocols. WMN uses Radio Aware Optimized Link State Routing Protocol (RA-OLSR) [11] [12] as optional.

The performance of reactive routing protocol depends upon the scenario as shown in [13] and, in particular, DSR works better than AODV in constrained situations where several CBR traffic sources are directed toward the same mobile destination.

In this paper we focus on multimedia traffic and, for this reason, we choose to use a DSR based protocol.

IV. TESTBED CONFIGURATION

To evaluate a comprehensive wireless mesh networking system, we built an experimental WMN on the third floor of the UCLA Computer Science building (Boelter Hall), as shown in Figure 2. The building is square shaped with an open space in the middle. On one side there is an external corridor that is partially separated from the open space by a metallic rail. The network is composed of eight computers (five laptops and three desktops) running Microsoft Windows XP SP2. Six of them act as MPs (implementing MCL) and the others as STAs. Specifically, two MPs are placed in the external corridor (see Figure 3), one in a side corridor, and three inside our laboratory, which is lightly partitioned. Instead, the two STAs are located at the edges of the WMN.

Each MP has one IEEE 802.11b wireless adapter installed whereas each MAP has two IEEE 802.11b wireless adapters installed. Focusing on MAPs, one of their adapters is linked with MCL and used to build the WMN with the MPs, the other one is utilized to allow the connection to the two STAs (see Figure 4), which are the source and destination of the network transmission. Both

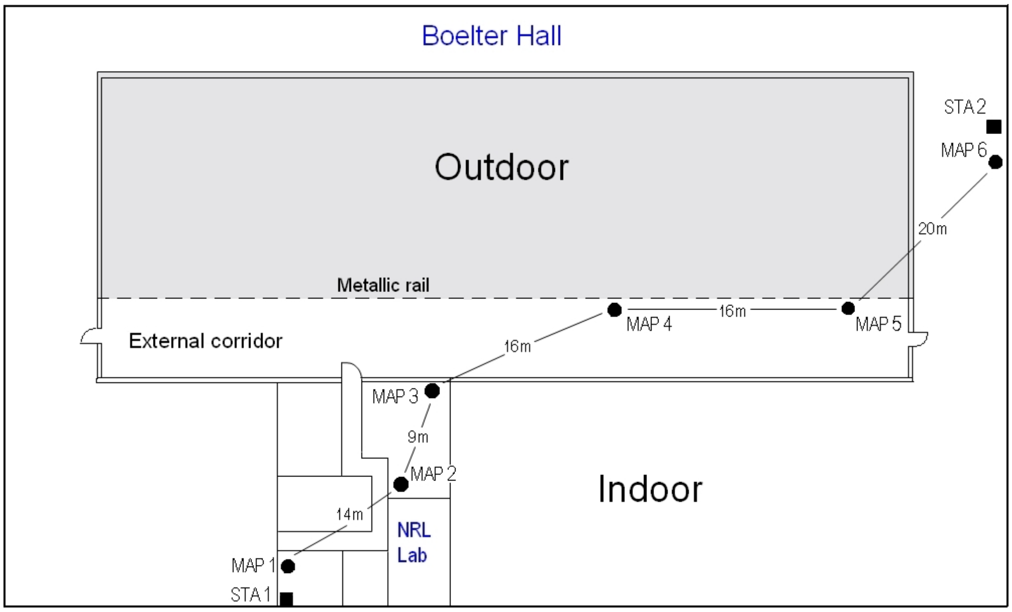

Fig. 2. UCLA - BH 3rd floor Laptops Deployment

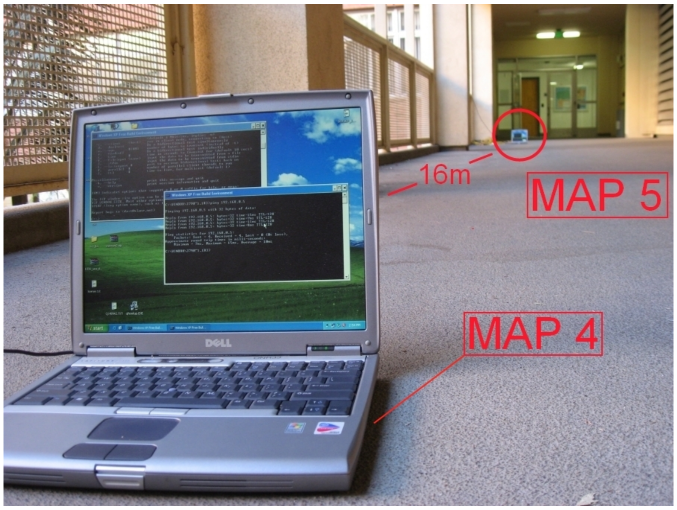

Fig. 3. Part of the Testbed

wireless interfaces use the same channel; this allows to simulate the use of just one interface shared by the infrastructure network (among MAPs and STAs) and the WMN.

The implemented WMN uses the MCL as described in the previous section. To this aim, we installed the MCL virtual adapter on each MAP. MCL allows computers to be linked through the same ad-hoc network using a routing protocol running on the 2.5 interlayer of the OSI model.

To monitor the effective multi-hop connection, we used the Microsoft Network Monitoring 2.0 software (NetMon), which is part of the Microsoft Mesh Toolkit. Thanks to a dedicated parser for MCL, we were able to analyze the connectivity and the performances of each MAP in our testbed.

We employed iPerf [15] to generate UDP traffic between the two STAs located at opposite extremes with respect to the WMN, with a variable number of MAPs (hops) in between, and with a variable data sending rate ranging from 1Mbit/sec to 5Mbits/sec. Furthermore, as many popular applications (e.g., FTP, HTTP, VoD) utilize TCP as their transport protocol, we have also evaluated scenarios where UDP and TCP-based flows coexist.

V. THE TESTBED AT WORK: PERFORMANCE EVALUATION

Before running the comprehensive set of experiments, we checked each single-hop link (STA1-MAP1, MAP1-MAP2, ..., MAP6-STA2) of the multi-hop path in order to ensure that the location of the various nodes allowed good reciprocal communications.

Each of the reported graphs is the result of the average among 30 experiments for each traffic configuration. Different experimental evaluations were run at different hours and during different days, yet, every time we started with a set of experiments we tried to have as homogeneous initial conditions as possible by testing them all, without long interruptions, one configuration after the other.

Figure 5 reports the quality of each link through the percentage of packet loss suffered by each single link

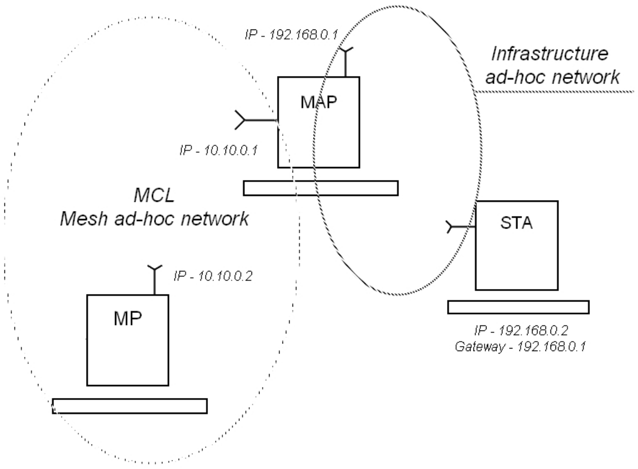

Fig. 4. MAP - STA connection

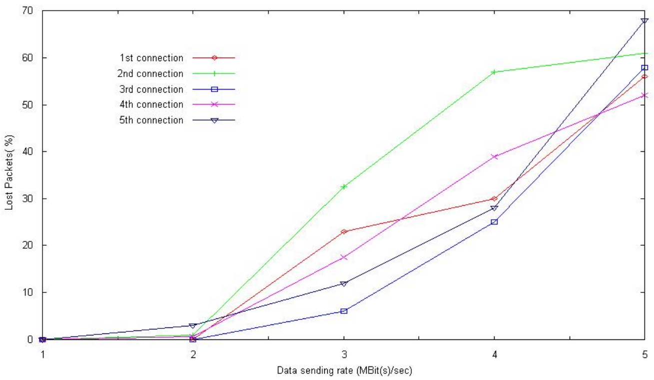

Fig. 5. Single-hop Link Quality with Single Flow Transmission

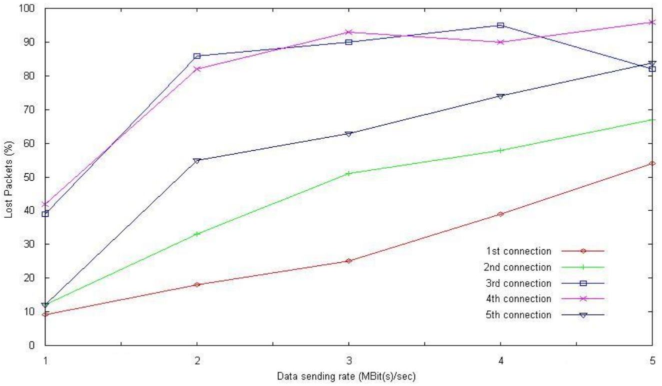

Fig. 6. Single-hop Link Quality with Multiple Flow Transmissions

when traffic is present only on that link; i.e., the first link is represented by the connection between MAP1 and MAP2, the second one goes from MAP2 to MAP3, and so on until the fifth link that connects MAP5 to MAP6. Different data sending rates for UDP-based flows are compared. As it is evident, all links present a good quality level until the data sending rate reaches the threshold of 3Mbit/sec; at that point, losses become excessively frequent.

Similarly, Figure 6 shows the packet loss percentage for each single link when traffic is contemporary present on all connections: in the same moment, a flow goes from MAP1 to MAP2, another one from MAP2 to MAP3, etc. In this case, interferences among the various connections worsen the transmission quality of all the links. Some links are more severely affected than others: longer links such as the third, the fourth, and the fifth (MAP3-MAP4, MAP4-MAP5, and MAP5-MAP6, respectively) present the highest packet losses. However, since the fifth link is located at the edge of the WMN, it experience less interferences than the other two even if it is the longest link in the WMN.

In Figure 7 we present the packet loss as a function of UDP's data sending rate and of the number of hops between source STA1 and destination STA2. Basically, in this configuration we consider multi-hop flows between the two STAs. As expected, connections established over one or two hops present results comparable with those in Figure 5, thus ensuring a good level of transmission quality and data sending rates up to 2Mbit/sec. Instead, when considering a three hop connection, only transmissions at 1Mbit/sec show acceptable packet loss percentages. Finally, connections exploiting four or more hops are featured with packet loss percentages that are unfeasible for any multimedia traffic.

These outcomes are coherent with measured jitter values shown by Figure 8. In fact, as for the packet loss, even the jitter increases with the number of hops; clearly, this is also because very few packets reach their destination.

As anticipated in Section IV, we also evaluate the scenario where a TCP and a UDP flow share the WMN. A 10 sec UDP flow is periodically started and stopped every 20 sec and is characterized by an increasing data sending rate (respectively from1Mbit/sec to 5MBit/sec). Figure 9 reports the throughput achieved by the two flows when they both utilize the same single-hop link for their transmissions. Clearly, every time the UDP flow starts sending packets its throughput quickly reaches the maximum available bandwidth; instead, TCP experiences several losses with consequent multiple reductions of its congestion window (and throughput). This is a well known consequence of UDP's lack of congestion control [14].

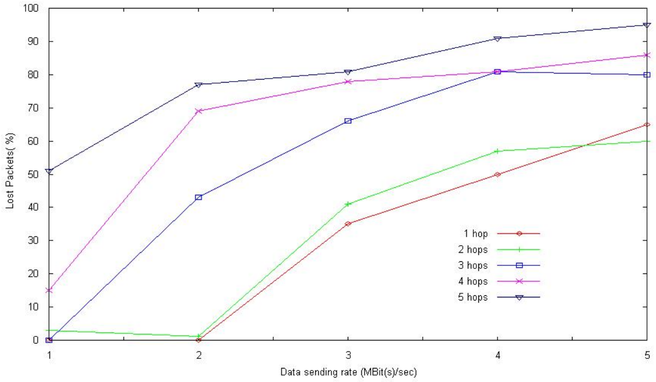

Fig. 7. Packet Loss

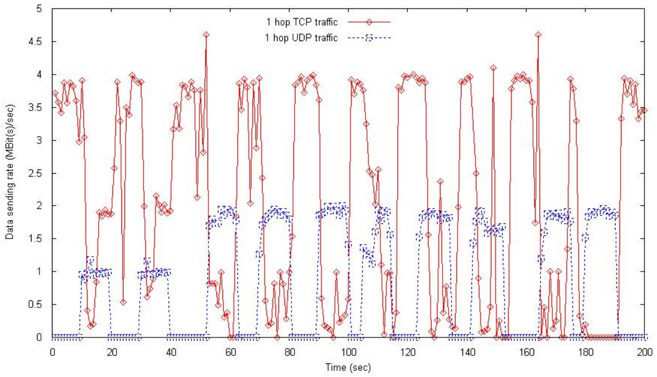

Fig. 9. TCP and UDP Flows Sharing the WMN; Same Number of Hops

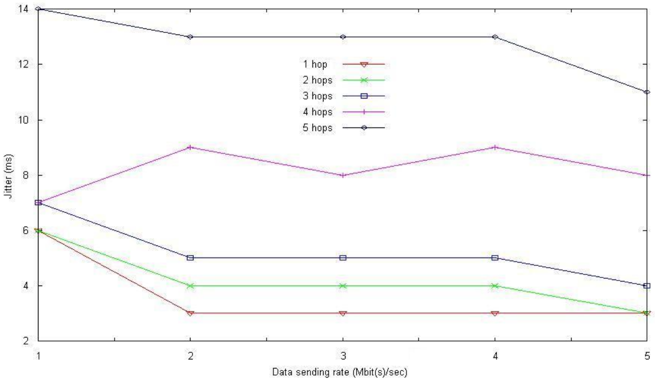

Fig. 8. Jitter

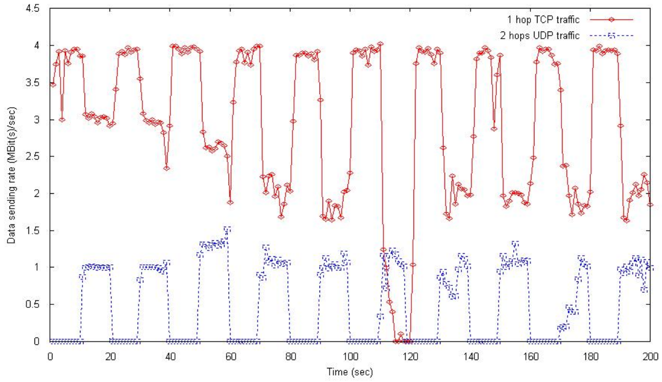

Fig. 10. TCP and UDP Flows Sharing the WMN; Different Number of Hops

Figure 10 shows the case where the number of hops in the WMN that have to be traversed by the UDP flow is increased to two. In this case, the longest route penalizes the UDP flow, reducing it actual throughput to about just half of its data sending rate and leaving more bandwidth to TCP. Even in this case, the outcome confirms a well known property (in wireless multi-hop scenarios): connections traversing a higher number of hops are slower than connections with shorter routes [16].

In summary, enjoying multimedia applications through common WMN technology seems to be limited to scenarios where communications involve very few hops, small bandwidth requirements, and absence of competing traffic on shorter paths. Needless to say, this is not what hoped for wireless mesh networking. Substantial efforts by the research community and the industry is hence needed to transform the current state of the art into a truly efficient, reliable, and flexible wireless networking option.

VI. CONCLUSION AND FUTURE WORK

In this work, we reported on the deployment of a real indoor testbed utilizing available WMN technology based on Microsoft MCL. This testbed was exploited to provide an original evaluation of the factual capability of this technology in supporting rich-media streaming (e.g., video on demand, teleconferences), which represents one of the most resource-consuming, yet more and more popular among users, kind of application.

Based on results presented in this paper, we can claim that with today's technology, WMN is far from being fully exploitable to support multimedia traffic streaming. Rich multimedia applications require higher performances at the MAC layer such as those promised by IEEE 802.11n [17]. Indeed, by adding the multiple-input multiple-output (MIMO) technology, signal processing, and smart antenna techniques, IEEE 802.11n should guarantee up to five times the bandwidth and up to twice the range of IEEE 802.11g.

Moreover, beside serving as a means to test and refine the practical applicability of WMNs, the testbed also allowed us to study many practical issues that inspired us future directions for this work. Indeed, we intend to develop techniques to help ad-hoc routing protocols in choosing high quality routes and to test them in a scenario with up to 32 MPs (as established in the 802.11s standard proposal), thus also increasing the number of possible paths and the interference traffic. Furthermore, we are currently modifying the source code of the Microsoft MCL in order to integrate the Hybrid Wireless Mesh Protocol proposed by IEEE 802.11s. Then, we want to evaluate how the traffic between STAs and MAPs impacts the backbone traffic among MAPs.

VII. ACKNOWLEDGMENTS

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