

An Experimental Study of Multimedia Traffic Performance in Mesh Networks

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Abstract

Performance evaluation and analysis of wireless networks is essential because testbed experiments facilitate a better understanding of network and application characteristics. This understanding of performance, in turn, results in robust protocol design. In this paper, we present an experimental study of multimedia traffic performance in mesh networks. We evaluate the performance of video and voice traffic through multi-hop wireless paths and study the capacity of the mesh network. We also investigate the impact of different traffic and network characteristics on application performance. The impact of different wireless network interface card configurations is examined, followed by our suggestions for how to improve performance. We believe our study is beneficial for both wireless network capacity planning and robust protocol design for wireless applications and services. Other researchers can also draw upon our traffic measurement experience for their own mesh testbed experiments.

1 Introduction

The growing deployment of wireless technology and infrastructure is enabling a variety of new applications. These applications require flexible and robust network support. For instance, multimedia applications, which include video streaming, VoIP and online gaming, often demand seamless real-time data delivery. These requirements, in turn, necessitate that both the application and the network be able to adapt to the highly variable nature of wireless channels. Evaluation and analysis of the performance of these applications on wireless networks therefore becomes increasingly critical so that the network and application characteristics can be better understood. Such understanding also facilitates robust protocol design for the future wireless Internet.

The majority of wireless research has been conducted using simulations which offer an efficient and flexible means to evaluate new protocols using fine-grained control. However, in simulations, MAC protocol models are often simplified, ideal wireless channels are assumed

without consideration of background noise and random interference, and unrealistic traffic traces are utilized. Consequently, evaluation through simulation may not reflect the performance obtained in real networks.

As a result of the inaccuracy of simulations, many researchers have begun deploying multi-hop mesh networks for use in wireless network protocol development and testing. Testbed experiments can be challenging due to the effort required to install, configure and manage the hardware [5]. In addition, performance results are often affected by the specific configurations and protocol settings. Given the significant number of possible parameters that can affect results, finding a representative set of parameter values is non-trivial. Furthermore, the highly varying characteristics of wireless links often lead to unstable and unrepeatable results. Significant effort is necessary to enable repeatable tests and to establish adequate methods for collecting and analyzing the testbed data.

In this paper, we present our experimental study of multimedia traffic performance in mesh networks. Multimedia applications are examined because they represent a growing percentage of Internet traffic and applications. These applications demand more stringent service quality with low delay and jitter. Specifically, we perform tests consisting of video streams and voice traffic over the UCSB MeshNet testbed (<http://moment.cs.ucsb.edu/meshnet>). We evaluate the performance of the delivery of the multimedia data through multi-hop wireless paths and study the capacity of the mesh network. We also examine the impact of different traffic and network characteristics on application performance. Specifically, we compare the performance of bursty video traffic with constant bit rate voice traffic. We also investigate the impact of different wireless network interface card configurations. We believe our study is beneficial in both wireless network capacity planning and protocol design. We describe our analysis methodology and utilities so that other researchers can draw upon our experience for their own mesh testbed experiments.

The remainder of this paper is organized as follows. Section 2 briefly introduces the UCSB MeshNet testbed and describes the set of tools we used for our experiments. Section 3 describes the experimental setup and the evaluation metrics. Section 4 presents the experimental results and performance analysis. Finally, Section 5 discusses our observation and concludes the paper.

2 UCSB MeshNet Testbed

The UCSB MeshNet testbed is a wireless mesh network deployed on the campus of UC Santa Barbara. The network consists of 25 nodes equipped with IEEE 802.11b wireless radios. The nodes are distributed on five floors of the Engineering I building. The purpose of the testbed is to evaluate protocols and systems designed for the robust operation of multi-hop wireless networks.

The UCSB MeshNet testbed consists of two different types of nodes. Our experiments are conducted on one type of node, called *Mesh Gateways*, which are off-the-shelf Intel Celeron 2.4GHz machines running Linux version 2.4.20. The machines use wireless utilities version 16 and the hostap driver for communicating with the Netgate 2511 PCMCIA 802.11b radios. The 802.11b radios operate in ad hoc mode and connect the wireless mesh nodes. Each node is also equipped with an Ethernet interface to provide Internet access to the mesh devices and to allow out-of-band management of the mesh gateway [5].

We utilize existing tools such as `iwpriv` to set the pseudo BSSID and lock the cell because otherwise BSSID changes occur frequently in the tests and significantly impact the results. `iptables` is also used for packet filtering and route configurations. To facilitate repeatable experiments and accurate data analysis, we also developed two utilities for network monitoring and diagnosis.

Link reliability test tool: We perform link reliability tests between node pairs. The goals are to 1) measure the link quality of individual hops, and 2) identify any asymmetric links. To test reliability, the packet delivery rate in both the forward and backward direction of a link are measured. The measurements are done by sending periodic broadcast packets and recording the number of packets successfully received at each neighbor during a given period of time. Broadcast packets are used because MAC layer retransmissions do not occur for broadcast packets and thus these packets can be used to estimate the raw packet delivery rate. A link is considered symmetric if the packet delivery rate on both the forward and reverse path is above 70%. We perform each test multiple times and identify node pairs that have reliable bi-directional links. We use these node pairs for our experiments. We also verify the reliability of the links before

and after each test run to ensure that the link quality is consistent with our long term measurements.

Time synchronization tool: In our performance analysis, time synchronization between the mesh nodes is needed for delay and bandwidth calculations. The multimedia traffic cannot be utilized itself because it uses UDP as the transport layer protocol. It is thus one-way, i.e., no ACKs are provided. Therefore, the packet transmission delay needs to be measured by the destination. Further, because asymmetric links frequently occur in wireless networks, round trip latency does not provide a consistent, accurate measurement of one-way delay. Therefore, time synchronization is critical for mesh testbed experiments.

We initially applied the Network Time Protocol (NTP) [4] to eliminate the clock skew among the mesh nodes. However, our results show that the NTP synchronization precision is tens of *milliseconds*. This level of accuracy is not sufficient for our data analysis. Thus, we developed a tool to calculate the time difference of two machines by utilizing the wired management links of the mesh nodes. These links connect to the local area network in the Engineering I building. Specifically, our tool transmits consecutive 4-byte probe packets that include the timestamp of the source node. Upon reception of these probing packets, the destination node records the timestamp and echos a 4-byte packet containing the time difference between the two timestamps. At the same time, the source also sends 4-byte probe packets to measure the round trip latency. The real clock difference between the two nodes is the difference transmitted by the destination minus half of the round trip latency. We repeat the tests ten times. Our measurements indicate that, in the local area wired network, the average round trip latency and the time difference calculation have less than $10 \mu\text{sec}$ error.

3 Experimental Setup

In this section, we describe our experimental setup, including the network configuration and traffic characteristics of both video and voice applications. We also explain the set of experiments we performed and the evaluation metrics.

3.1 Network Topology

We utilize the reliability test tools described in Section 2 to identify the node pairs with the most reliable bi-directional connections. From the results, we select a sequence of five nodes that form a four-hop path. Two of the selected nodes are located in neighboring labs on the second floor and a third node is across the hallway. The

other two nodes are located on the third floor. We then update the routing tables of these nodes with static route entries to form paths from one to four hops.

3.2 Application Traffic

We examine the performance of multimedia traffic over the mesh network. Specifically, we use UDP video and voice streams recorded with `RTPTOOLS` [1]. We use `rtpplay` for streaming at the source node and `rtpdump` to record the packets received at the destination. Voice traffic follows a constant bit rate (CBR) with an 80-byte voice packet transmitted every $10ms$ using G.711 codec, resulting in a data rate of $64kbps$. Video traffic, on the other hand, tends to be more bursty. Figure 1 plots a 10-second sample trace of a video source. The source transmits between two and three frames of data every second, where each frame consists of between three and seven $1KB$ packets. These packets are typically sent within a couple of milliseconds. H.261 codec is used for the video traffic and the average bit rate is $128kbps$.

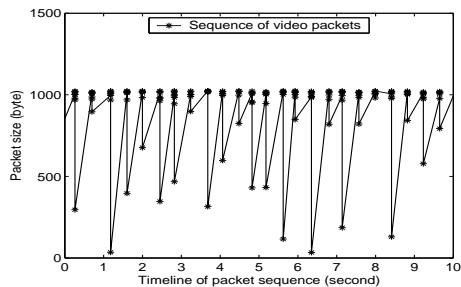


Figure 1: Sample video packet sizes transmitted by the source.

3.3 MAC Layer Configurations

In our experiments, all nodes operate in ad hoc mode on Channel 6 and use a static routing topology. The primary configuration parameters that we vary during the experiments focus on the wireless network interface cards. Specifically, we perform tests with the card operating at a *fixed* data rate ($2Mbps$) and *auto* rate (auto-rate adaptation at 1, 2, 5.5 and $11Mbps$). In the auto-rate tests, the data rate increases as the number of successfully delivered packets increases. Conversely, the transmission rate decreases when the number of packet errors increases. This mechanism is called Auto Rate Fallback (ARF) and is specified in the IEEE 802.11b standard [6]. We also investigate the impact of both the Request To Send/Clear To Send (RTS/CTS) mechanism and the maximum number of retransmissions. By default, the maximum number of retransmissions per packet is set to seven for small packets and four for large packets. RTS/CTS is recommended for large data packets¹.

¹There is no specific RTS/CTS threshold value indicated in the IEEE 802.11b standard.

3.4 Experiment Scenarios and Metrics

Our tests are performed at night so that the impact of random interference (e.g., background noise, people and traffic on other wireless networks) is minimized. We also collect results during the day to examine the impact of these factors.

We conduct the following set of experiments:

1. We examine the impact of auto-rate adaptation of the wireless card by varying the data rate setting to be either fixed or auto-rate. In this scenario, the RTS/CTS is disabled and the maximum MAC retransmission number is set to seven.
2. We study the impact of RTS/CTS by comparing the performance with the RTS/CTS feature either enabled or disabled. In this scenario, the data rate is fixed at $2Mbps$ and the maximum number of retransmissions is seven.
3. We investigate the impact of the number of transmissions by varying the maximum retransmission value. In this scenario, the RTS/CTS is disabled and the data rate is fixed.

The metrics used to evaluate performance are:

1. **Packet latency:** the end-to-end packet transmission latency.
2. **Packet loss rate:** the percentage of packets that are not successfully received at the destination.
3. **Inter-flow fairness:** indicated by the variation of delay or loss among competing flows.
4. **Packet jitter:** indicated by the variation of inter-arrival latency for packets of individual flows.

4 Experiment Results

In this section, we evaluate the performance of video and audio traffic through multi-hop wireless paths and study the capacity of the mesh network. We also examine the impact of different traffic and network characteristics on the application performance. Further, we show the impact of different wireless network interface card configurations.

4.1 Capacity

Table 1 shows the number of video and voice flows that the mesh network supports as the number of hops increases. For video data, we consider less than 1% packet loss acceptable. If a more resilient coding scheme is utilized, it is possible that a higher loss rate will be tolerable. For voice data, we consider $150ms$ as the interactive voice delay threshold [3]. We tested the performance with the the NIC set to a fixed data rate ($2Mbps$) and with auto-rate adaptation.

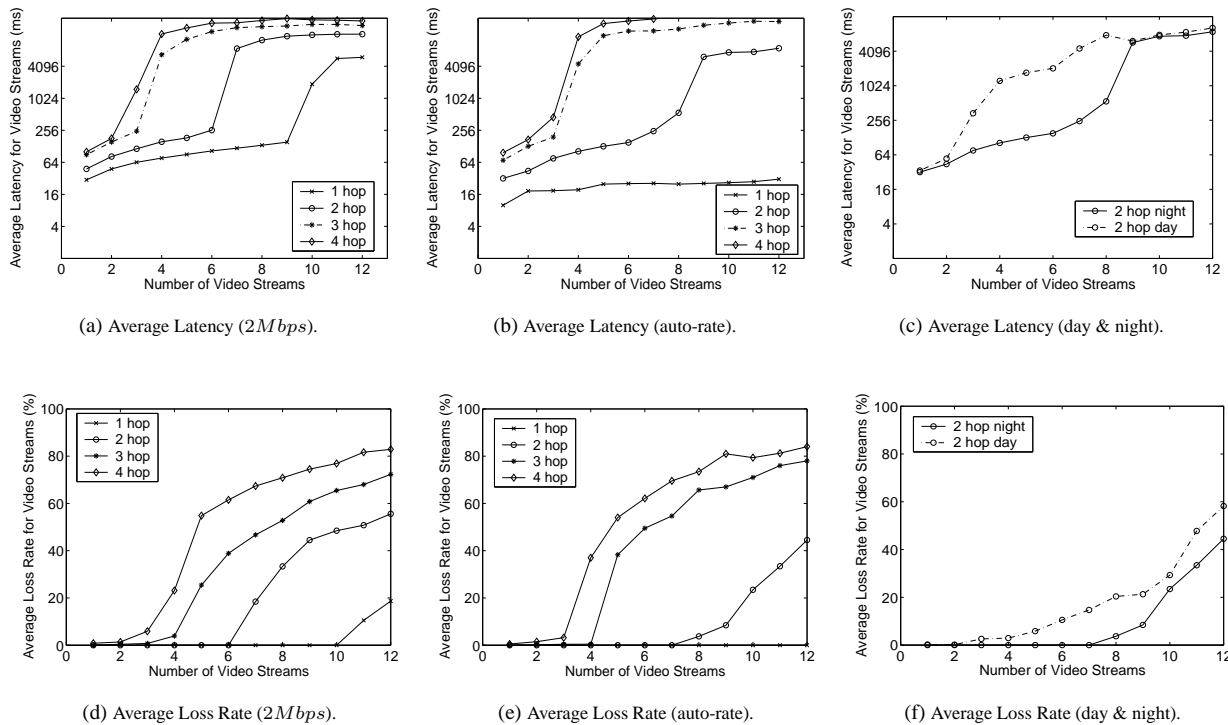


Figure 2: Performance with increasing number of video streams.

Table 1: Number of supported, concurrent flows at acceptable quality.

Traffic	Video				Voice			
	1	2	3	4	1	2	3	4
Auto	30	9	3	2	11	6	3	2
Fixed (2Mbps)	10	6	3	2	11	4	3	2

Intuitively, the network should support more voice traffic flows than video traffic because voice uses a lower data rate. However, as can be seen in Table 1, this is not the case. Instead, the packet sending rate plays a more important role in determining the capacity. Specifically, voice traffic has a higher packet generation rate of 100 pkts/second, while the bursty video traffic has an average rate of about 16 pkts/second. The higher sending rate leads to network congestion, while the packet size has negligible impact on the number of supportable flows in the network. To verify the impact of packet sizes, we also performed experiments with 200 byte voice packets. This results in a bit rate of 160kbps. The results indicate that the same number of flows are supported regardless of whether the rate is 64kbps or 160kbps.

Figure 2 shows the average packet delivery latency and loss rate for video traffic with a fixed 2Mbps data rate (Figures 2(a) and (d)) and auto-rate (Figures 2(b) and (e)). We do not include the results for voice traffic because they are similar except that voice traffic in general incurs low delivery latency due to small packet sizes.

We observe that as the length of the transmission path increases, the performance degrades and the latency and loss rate increase. However, the increase is non-linear due to the increased interference from neighboring nodes. The network capacity is constrained by the number of hops. From the results, we also observe that increasing the transmission rate of the card does not necessarily increase the capacity. For instance, the number of flows supported with the auto-rate feature (with maximum rate = 11Mbps) is close to that of the fixed data rate (2Mbps) in multi-hop scenarios, especially for voice flows with a large hop count. This result occurs because of the increased contention from neighboring nodes when the path length increases. With more packet contention and subsequent packet loss, the card will automatically fall back to a lower transmission rate.

In our experiments, we notice that the auto-rate adaptation follows a slow-start-like process. All nodes operate at the lowest data rate initially. We also occasionally observe a surprisingly low video flow delivery rate for a small number of flows in the auto-rate scenario. This is because auto-rate does not always succeed in adapting to a higher transmission rate when traffic is bursty. However, once the card succeeds in adaptation, a close-to-optimal throughput of about 6Mbps can be achieved [2].

Figures 2(c) and (f) compares the performance obtained during the day and at night for video flows traversing two hops with auto-rate. Interestingly, although our test nodes operate on a different channel than the other

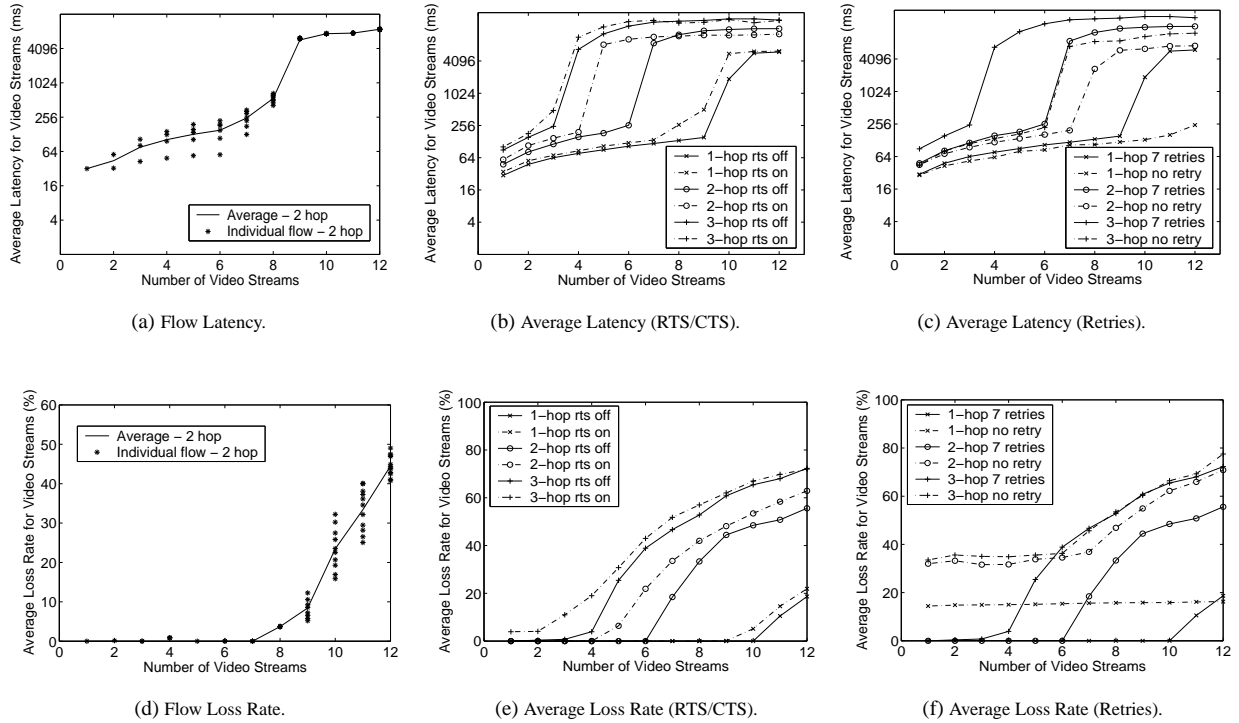


Figure 3: Performance with increasing number of video streams.

wireless networks in the building, we notice random interference and background noise during the day that significantly impacts the results.

4.2 Inter-flow Variation

Figures 3(a) and (d) show the fairness between competing video traffic flows when the network is operated in auto-rate mode. We notice that the latency variation among competing flows is significant when the network is not saturated. Flows started a couple of seconds after the first flows experience up to three times more latency than earlier flows. When the network is congested, the loss rate of the flows exhibits similar trends. As the path length increases, the variation becomes more significant due to the inter-flow contention between neighboring nodes. The same patterns with voice data are also observed during our experiments. These results indicate the phenomena of “channel capture” by earlier admitted flows resulting in unfairness to later flows [7].

4.3 Intra-flow Variation

Figure 4 illustrates the per packet delay for one individual flow on a 2-hop connection. The gray line indicates the delay when the network is lightly loaded with four concurrent flows. The delay variation is in the range of $5ms$ to $200ms$ with an average of $48ms$. The black line indicates the delay when the network is more heavily

loaded with eight concurrent flows. Hence there are more significant variations in the range of $6ms$ and $1200ms$ with an average of $412ms$. This indicates that with different channel conditions, traffic jitter could severely impact the received video/voice quality.

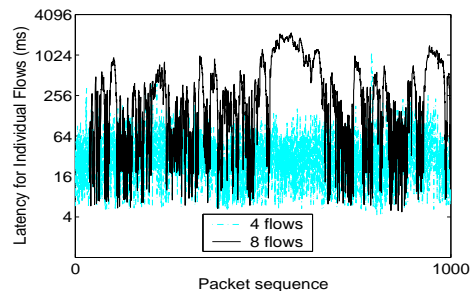


Figure 4: Intra-flow packet variation.

4.4 Impact of RTS/CTS

RTS/CTS is recommended in the IEEE 802.11 standard to eliminate the hidden terminal problem. The standard also suggests that for small packets RTS/CTS should not be utilized because of its extra overhead. For larger packets, RTS/CTS should be beneficial as a collision avoidance mechanism. Figures 3(b) and (e) show the impact of RTS/CTS by comparing the performance of video traffic with RTS/CTS enabled and disabled. The results indicate that even with large video packets, RTS/CTS does not usually offer a performance improvement in terms of

reducing latency and loss. On the contrary, it may actually limit the capacity of the network. For instance, Figures 3(b) and (e) show that in the 2-hop scenario, only four flows achieve satisfactory quality when RTS/CTS is enabled, while the network can support up to six flows when this feature is disabled. Our results suggest that RTS/CTS should not be used for multimedia traffic.

4.5 Impact of MAC Retransmissions

Figures 3(c) and (f) indicate the effect of changing the maximum number of MAC layer retransmissions on the delay and loss rate of the video traffic. A small maximum retransmission value reduces the transmission latency over each hop, as shown in Figure 3(c). Such reduction subsequently increases the capacity of the network if latency is the primary metric in consideration. The introduction of MAC retransmissions also significantly improves the packet delivery rate. As seen in the one hop scenario in Figure 3(f), the loss rate when no retransmissions are enabled is constant, indicating possible background noise and interference. When retransmission is enabled, the loss rate significantly drops. However, there is no one ideal value for the maximum number of retransmissions. When the network becomes congested, the loss rate with no retransmissions is actually no more than that with a maximum of seven retransmissions. The difference also varies with the number of hops. Hence, investigation of the relationship between the maximum number of retransmissions and the number of hops of the path would help to find an optimal value to achieve better performance.

5 Conclusions

In this paper, we have presented our experimental study of multimedia traffic delivery in the UCSB MeshNet testbed. We have evaluated the performance of video and voice traffic through multi-hop wireless paths and studied the network's capacity. We also examined the impact of different traffic and network characteristics on the performance. To summarize, we have made the following observations:

- The capacity of the network is constrained by the number of hops in the transmission path.
- The number of flows supported by the network is mostly heavily influenced by the packet sending rate, not by the data rate or packet size.
- Auto-rate adaptation does not always lead to capacity improvement when bursty traffic is present.
- Channel capture can result in unfairness among competing flows.
- Packet jitter variations can be significant in current 802.11b networks. Solutions are needed to dampen the variation for real-time traffic delivery.

- RTS/CTS does not typically help in improving performance of real-time traffic.
- Finding an optimal value for the maximum retransmission number may help improve performance.

We believe our study is beneficial for both wireless network capacity planning and protocol design. We have described our analysis methodology and utilities so that other researchers can draw upon our experience for their own mesh testbed experiments. We plan to continue our work studying experimental results obtained through our testbed. Specifically, we want to explore the techniques of reducing packet jitter in multimedia delivery and apply more advanced codec schemes and subjective evaluation methods to our traffic analysis.

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References

- [1] Henning Schulzrinne at Columbia University. RTP Tools (Version 1.18). <http://www.cs.columbia.edu/IRT/software/rtpools/>.
- [2] J. Jun, P. Peddabachagari, and M. Sichertiu. Theoretical Maximum Throughput of IEEE 802.11 and its Applications. In *Proceedings of the IEEE International Symposium on Network Computing and Applications*, pages 249–257, Cambridge, MA, April 2003.
- [3] C. Lin, H. Dong, U. Madhow, and A. Gersho. Supporting real-time speech on wireless ad hoc networks: inter-packet redundancy, path diversity, and multiple description coding. In *Proceedings of the ACM International Workshop on Wireless Mobile Applications and Services on WLAN Hotspots (WMASH)*, pages 11–20, New York, NY, 2004.
- [4] D. L. Mills. Internet Time Synchronization: The Network Time Protocol. In *Global States and Time in Distributed Systems*. IEEE Computer Society Press, 1994.
- [5] K. Ramachandran, K. Almeroth, and E. Belding-Royer. A Novel Framework for the Management of Large-scale Wireless Network Testbeds. In *Proceedings of the 1st Workshop on Wireless Networks Measurements (WinMee)*, Trentino, Italy, April 2005.
- [6] IEEE Computer Society. IEEE Standard for Wireless LAN-Medium Access Control and Physical Layer Specification, November 1999.
- [7] N. Vaidya, P. Bahl, and S. Gupta. Distributed Fair Scheduling in a Wireless LAN. In *Proceedings of the International Conference on Mobile Computing and Networking (MobiCOM)*, Boston, MA, August 2000.