High-speed wireless backbones: measurements from *MagNets*

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***Abstract*— The long-standing vision of ubiquitous Internet access requires high-speed wireless networks that sustain 100 Mbps or more. While existing hardware already supports these speeds and they are available at single access points, measurement studies of existing mesh or multi-hop WiFi networks that cover and span larger areas report effective throughputs that are one or two orders of magnitude lower. We ask the question whether we can not already build high-speed wireless network that sustain high rates. To answer this question, we have built the *MagNets* high-speed WiFi backbone in the heart of Berlin. This paper presents an experimental evaluation of the single and multi-hop performance in terms of throughput, jitter, delay, packet loss, and assesses the impact of environmental factors on these parameters. Our results indicate, e.g. that some links achieve a sustained UDP throughput of up to 62 Mbps using off-the-shelf hardware supporting Super-AG modes, whereas others are limited to $4-5$ Mbps due to interfering networks. In contrast, we show that the link performance is largely unaffected by environmental factors, such as day/night or social events (i.e. *2006 FIFA World Cup* semi-final and final matches).**

I. Introduction

Wireless networks have the potential to revolutionize the society's perception of the Internet. Once we are able to combine the inherent ubiquity of wireless communication with high speeds, wireless access networks will eliminate the Digital Divide, provide connectivity to rural areas and developing countries where fiber would be excessively expensive.

Unfortunately, existing wireless networks draw a dark picture on the performance of wireless networks. Mesh networks, such as the MIT roofnet [3] or the TfA network in Houston, Texas [4] show mostly single-digit link throughputs, even though the hardware would be able to sustain at least 54 Mbps raw throughput. Moreover, the throughput is severely degraded if data has to be forwarded over multiple wireless hops. Based on these numbers, a plethora of proposals have been made for new protocols that achieve a higher throughput, e.g. new TCP variants for wireless networks.

The question we are trying to answer is simply whether it is possible to deploy high-speed wireless networks with existing off-the-shelf technology in the first place - and search for alternative protocols where needed. To shed light onto the capabilities and limitations of wireless access networks and to leverage our knowledge of wireless technology from its infancy, we are deploying the *MagNets* testbed in the city of Berlin [9], [8]. A core component of this next-generation metropolitan wireless access network is a high-speed WiFi backbone that consists of off-the-shelf Access Points (AP) that support a raw link throughput of 108 Mbps, directional antennas and routers that allow simultaneous link activations to transmit data in parallel over multiple links. By performing a comprehensive experimental performance study, we make the following contributions.

First, we assess the ability to support high transmission rates (at both transport and application layer) over the WiFi backbone. In particular, we provide a detailed performance evaluation of the throughput, delay, jitter and packet loss. We measure these parameters over single links as well as over multiple hops, using the basic 802.11 mode as well as with the Super-A/G modes available from the off-the-shelf WiFi cards. We anticipate that the results vary significantly as the links are highly diverse in terms of distance, technology (802.11a or g) and the degree of interference varies among the different locations. Therefore, the results yield valuable insights for related deployments.

Second, we study the impact of CBR (using VoIP traffic) and VBR (using Video on Demand (VoD) traffic) traffic over *MagNets* obtained with a single flow and multiple concurrent flows. These measurements extend the above experiments by assessing the backbone behavior under realistic application-layer traffic and by measuring the quality perceived by the application.

Finally, we study the impact of environmental factors on the link characteristics. In particular, we perform periodic measurements over 24 hours and compare the detailed link characteristics. Moreover, we perform similar measurements during the main events of the World Soccer Championship in Berlin (during July 2006) to investigate whether such social events have a noticeable impact. We anticipate that the backbone links are largely unaffected by environmental factors even though we consistently measure slight variations in the link characteristics. To the best of our knowledge, this work extends the results present in literature in that: (i) *MagNets* is an unique network environment in which it is possible to study several issues concerning multihop and heterogeneous wireless-wired networks; (ii) a careful performance measurement activity provides a more clear understanding regarding WiFi urban backbone; (iii) a long term analysis

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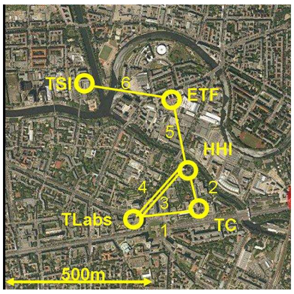
TABLE I

MagNets WiFi Backbone.

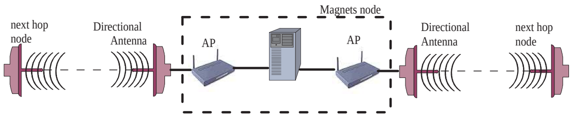
(a) *MagNets* backbone in Berlin.



(b) Router characteristics.

Processor	IntelP4, 3 GHz
Memory	1 GB
HDD	80 GB
OS	Linux, 2.6.15 Kernel
Routing	OSPF

(c) *MagNets* node.



of the performance allows to evaluate the impact of external factors; (iv) an analysis of the performance with concurrent flows of real time-like traffic is useful to assess the behavior of new applications on such network. It is worth noting that the traces we collected during this work are publicly available at [14].

The rest of the paper is organized as follows. Section II introduces the network configuration and the methodology we used for the measurements. Sections III, IV and V present the results obtained by the experimental analysis. Section VI discusses the related works underlining the differences with our work. A discussion on the main findings, some final considerations, and an overview of the ongoing work are presented in Section VII.

II. Scenario, objectives and methodology

A. Backbone description

The *MagNets* project aims at deploying a next-generation wireless access network architecture. Within this network, the high-speed WiFi backbone connects 5 high-rise buildings in the heart of Berlin (see Figure I(a)). The backbone is composed of 5 nodes. A node is depicted in Figure I(c): it consists of a PC-based router and multiple attached Access Points (AP). The key parameters of the PC are given in Table I(b) of Figure I. The PC has n network interface cards, each connecting to one AP. The APs contain Intel IXP420@266 MHz (indoor) and IXP425@533 MHz (outdoor) programmable network processors and Atheros $5213/5112$ chipsets [1] for their WLAN interfaces. The APs run a proprietary operating system called LC.OS [11]. The resulting relevant link characteristics and the router details are described in Table II.

The backbone achieves end-to-end high transmission speeds up to 108 Mbps by three means. First, each link can be activated individually and in parallel because the backbone router contains multiple network interface cards. Therefore, as our measurements will show, multi-hop throughput degradations known from mesh networks [6] can be avoided. Second, directional antennas ensure a high signal level to bridge the distances but also reduce the interference with other links. Third, the APs feature two proprietary protocols to enhance the throughput beyond the 54 Mbps supported by 802.11a/g termed *Turbo Mode* and *Burst Mode* that can be enabled optionally. *Turbo Mode* doubles the channel from 20 MHz to 40 MHz. While, using *Burst Mode*, the sender only waits for the shorter SIFS (Short Inter-Frame Space) after a successful data exchange instead of the longer Distributed Inter-Frame Space (DIFS) specified in 802.11. According to the vendor, the modes should result in a performance enhancement of 10 Mbps for *Burst Mode* and a throughput doubling for *Turbo Mode* [10]. These modes are expected to boost the backbone performance without negative impact due to the independent link scheduling and the use of directional antennas. For general (mesh) networks, however, *Burst Mode* can lead to severe unfairness and *Turbo Mode* interferes with all other channels in the 2.4 GHz spectrum because it must be centered around channel 6 to stay within the allotted frequency band.

B. Objectives

In our previous work [8] we have investigated the performance of some of the links composing the *MagNets* backbone using both TCP and UDP traffic with two constant bitrates each. Using only one link, we also briefly investigated the impact of variable bitrate traffic and of *Turbo-* and *Burst Modes* simultaneously activated. Such work was meant to report the potential of this testbed explaining the constituent blocks and showing some experimented results.

In this paper, instead, we present a more deep and complete analysis of the performance of the backbone. Our aim is to evaluate the impact of different variables on the performance of the backbone. As already remarked in our previous work, the *MagNets* testbed allows for a wide set of parameters to be tuned, yielding an ample variety of aspects to be investigated. Among all the possible experimentations, in this work we focus on the following :

- Backbone parameter impact (Section III). This is to investigate the best operating conditions of the links and is divided in the following subsections:
  - Performance achieved by each link, with high bitrate traffic and no enhanced modes.
  - Performance achieved by each the using *Turbo Mode*, *Burst Mode*, and *Turbo*+*Burst Mode*.
  - TCP performance over multi-hop paths.
  - Interference caused by enhanced AP modes to parallel link transmission.
- Traffic characteristic impact (Section IV). These experimentations are meant to assess how the performance estimated in the previous sections are impacted by different kinds of traffic. Section IV is divided in the following subsections:
  - Different combinations of IDT and PS producing different traffic loads.

– Multiple concurrent CBR and VBR flows.

- Environmental factor impact (Section V). This analysis is aimed to evaluate the stability of the performance on a long term horizon and with external causes of interference. This analysis is divided as follows:
  – Natural environmental factors (i.e. day and night).
  – Human related environmental factors such as very popular social events (i.e. FIFA World Cup matches).

C. Methodology

We opt for an active measurement approach to investigate the performance of the *MagNets* backbone at both transport and application layer [8]. Probing traffic is generated via two tools: Iperf [12] and D-ITG [15]. Iperf is a well-known tool to create TCP and UDP traffic load. D-ITG is a synthetic traffic generation platform that allow to choose custom Inter Departure Time (IDT) and Packet Size (PS) for probing traffic and also provides analysis tools to study QoS parameters. D-ITG is used for long lasting measurements that affect multiple links (e.g. 24h measurements presented in Section V-A) and to collect application-level statistics (jitter, delay, packet loss) by using traffic with peculiar characteristics. The measurements, taken from May to October 2006, resulted in about 80 GB of data traces that are publicly available [14].

III. Link measurements

A. Baseline results

As a baseline for the subsequent high-speed measurements, we first assess the performance of each link individually in its basic configuration, i.e. with 802.11a/g as defined in the standard. We generate UDP traffic for 600 seconds at the source node using Iperf at 70 Mbps, which is well above the sustained data rate and therefore saturates the link. At the receiving node, packets are captured using tcpdump. To calculate the bandwidth, the raw trace is sampled at 50 ms interval and the bytes received in this interval are summed up.

Tables III(a) and III(b) show the mean and standard deviation of throughput respectively. Link 1 outperforms the others with an average throughput of 31.3 Mbps. Moreover, the low standard deviation of 0.9 Mbps indicates that the link is very stable. Next, links $2-4$ have an average throughput between 6.2 and 12.2 Mbps. These links operate in the 2.4 GHz range; the throughput degradation is attributed to interference. Finally, links 5 and 6 are the weakest links, with an average bandwidth of 4.3 and 5.4 Mbps respectively. Link 5 has strong interference because the ETF building is lower than the others, and link 6 spans a much larger distance with 930m. Thus, we conclude that the link characteristics vary significantly even though they have been measured in the same testbed.

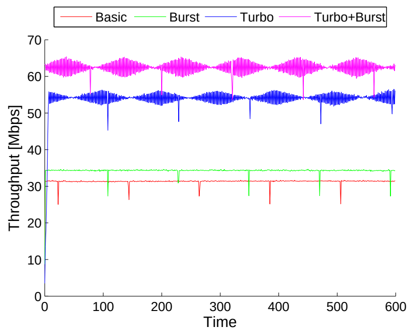
B. Enhanced modes

Here, we assess the impact of *Turbo*- and *Burst Mode* on the link performance using Iperf. Even though the reference manual indicates a doubling of the throughput via *Turbo Mode* and an increase of 10 Mbps with *Burst Mode*, it is not obvious how these modes impact the link characteristic of *MagNets*.

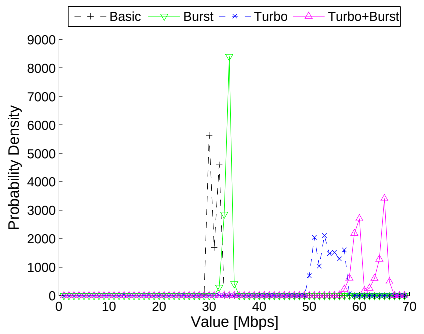
TABLE II

Link characteristics of the *MagNets* WiFi backbone.

	Link	Length	Freq	Prot
1	TLabs-TC	560 m	5 GHz	802.11a
2	TC-HHI	330 m	2.4 GHz	802.11g
3	TLabs-HHI1	520 m	2.4 GHz	802.11g
4	TLabs-HHI2	520 m	2.4 GHz	802.11g
5	HHI-ETF	520 m	2.4 GHz	802.11g
6	ETF-TSI	920 m	5 GHz	802.11a



(a) Timeplot.

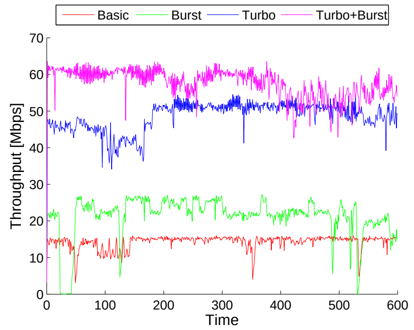


(b) PDF.

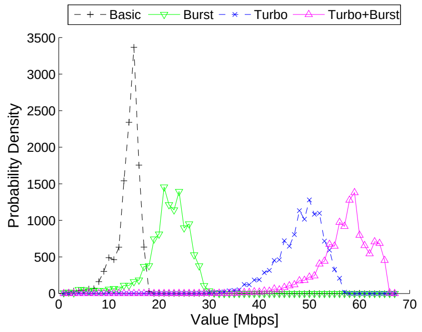
Fig. 1. Influence of enhanced modes on UDP Throughput of link 1.

Figure 1(a) and 1(b) show the throughput over time and the throughput distribution for link 1. The *Turbo*- and *Burst Mode* increase the throughput on link 1 significantly. Compared to the basic mode (31.3 Mbps), the throughput increases with *Burst Mode* to 34.2 Mbps. *Turbo Mode* boosts the throughput to an average of 53.8 Mbps. Finally, with both modes enabled, the average throughput reaches 62.4 Mbps! Quite interesting are the oscillating throughput patterns over time when *Turbo Mode* is enabled. We attribute this pattern to the Dynamic Power Selection that searches for the optimal power. Thus, we conclude that link 1 matches the original specifications and expectations of *Turbo* and *Burst Mode*.

Link 3 also shows throughput gains with *Turbo*- and *Burst Mode*. The corresponding rates are 8.4, 14.2, 39.1, and 50.3 Mbps. Note here that the improvement with *Turbo Mode* is more than twice the base rate. The distribution is more spread with the modes enabled than with the base mode. The variations occur in both short time ranges (seconds) as well as over 10s of seconds. We performed the same experiments



(a) Timeplot.



(b) PDF.

Fig. 2. Influence of enhanced modes on UDP Throughput of link 3.

TABLE III

INFLUENCE OF TURBO- AND BURST MODE ON UDP THROUGHPUT.

(a) Mean throughput (Mbps).

Link	1	2	3	4	5	6
Basic	31.3	12.2	8.4	6.2	4.3	5.4
Burst	34.2	14.1	14.2	12.8	4.5	5.7
Turbo	53.8	22.3	39.1	38.4	6.2	12.7
Both	62.4	24.2	50.3	51.2	8.4	13.8

(b) Stdev (Mbps).

Link	1	2	3	4	5	6
Basic	0.9	8.2	1.0	2.1	3.2	2.1
Burst	1.2	8.6	2.1	3.0	4.1	3.3
Turbo	3.6	14.5	5.8	5.3	5.3	8.2
Both	1.7	18.2	4.9	5.7	6.0	9.5

with all other links. The results were comparable to link 3. However, the detailed improvements varied over time and with the links. Given that the performance was significantly improved with *Turbo* and *Burst Mode* enabled, we argue that the MagNets backbone is able to support a substantial amount of traffic. However, the dynamic variations may require a priorization of the traffic.

C. Multi-hop

Here, we present initial measurements on the *MagNets* backbone that point at issues that have to be addressed for multi-hop wireless networks. In the following experiments, we use the topology shown in Figure I(a) but without links 3 and 4. The resulting topology is linear, with a maximum of 4 hops.

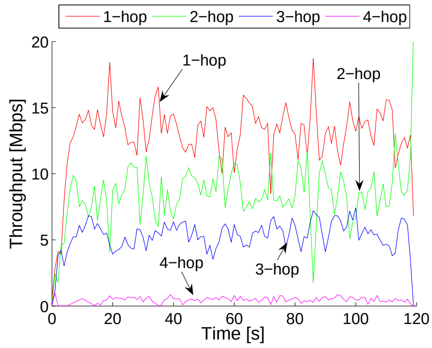


Fig. 3. Multi-hop TCP measurements.

An important issue in wireless multi-hop networks is fairness. It is well known that the throughput of flows in multi-hop wireless networks is biased towards flows which traverse few hops [6]. Multiple reasons are responsible for this bias. First, in CSMA/CA networks with omni-directional antennas, flows that traverse n hops must contend n times for the media, leading to a significant degradation if the nodes are always backlogged. Second, TCP intrinsically adheres to proportional fairness, i.e. flows with a larger RTT obtain a lower throughput. Both factors can accumulate and lead to entire starvation of flows. Figure 3 shows the fairness problem in *MagNets*.

We inject TCP traffic into the backbone at TLabs targeted to all other nodes. The y-axis shows the measured throughput as a function of the time. Two observations are important. First, the use of directional antennas and the ability to send and receive at the same time mitigates unfairness at the MAC and PHY layer. Therefore, unlike in the scenarios reported in [6], all flows have a throughput > 0. However, second, the low throughput of links 5 and 6 and the large RTT lead to a dismal performance of the 3- and 4-hop flow. The throughput is only a fraction of the corresponding link throughput. An operator may at this point decide to limit the rate of the 1- and 2-hop flows to increase the throughput of the multi-hop flows within the mesh to allow users at ETF or TSI to obtain a higher throughput. Our measurements emphasize the need for network-wide traffic control to ensure a fair and efficient resource usage in wireless multi-hop networks.

D. Twin Links Analysis

A particular feature of the backbone are 2 parallel links between T-Labs and HHI (links 3 and 4). Having two parallel links can be useful in load balancing scenarios, for redundancy reasons, and for intelligent routing strategies. Also, multipath applications can benefit from such configuration. In addition, two parallel links can reach higher throughput. Therefore, a careful performance analysis of these two link is needed because, in wireless scenarios, interferences play an important role.

First, we remark that, even in the case of orthogonal channels (e.g. channel 6 and 13 in IEEE 802.11g), some interference is expected. However, it is worth to assess the

TABLE IV

TWIN LINKS UNDER SIMULTANEOUS ACTIVATION.

(a) Per-link throughput (Mbps).

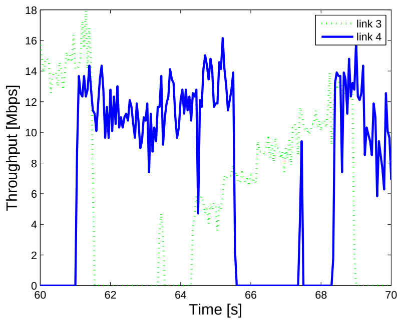
Link	Basic	Burst	Turbo	Turbo+Burst
3 UDP	8.4	13.0	19.0	23.1
4 UDP	6.2	6.9	20.1	22.8
3 TCP	7.3	14.4	16.9	23.0
4 TCP	5.8	9.0	14.2	27.0

(b) TCP RTT (ms) and retransmissions (%).

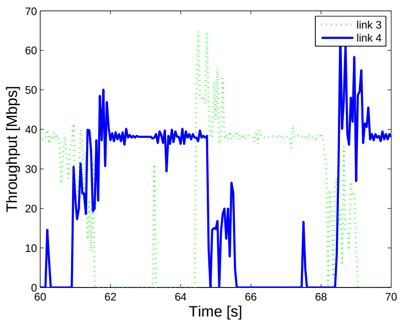
Link	Basic	Burst	Turbo	Turbo+Burst
3 RTT	56.2	28.8	23.8	15.1
4 RTT	71.2	45.5	26.4	14.0
3 retr.	0.21	0.19	0.18	0.17
4 retr.	0.22	0.20	0.21	0.16

impact of such interference on the application layer throughput in order to quantify the net gained obtained by deploying two parallel wireless connections on orthogonal channels.

Second, with 802.11g, *Turbo Mode* runs only on channel 6. Therefore a very high level of interference is expected. However, also in this case, it is interesting to evaluate the impact of the interference on the application layer throughput.



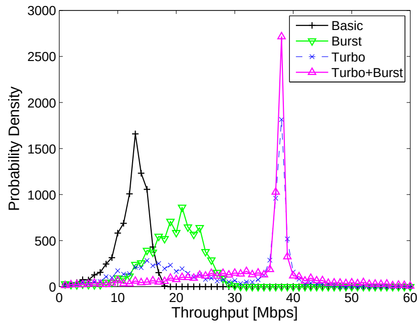
(a) Basic Mode.



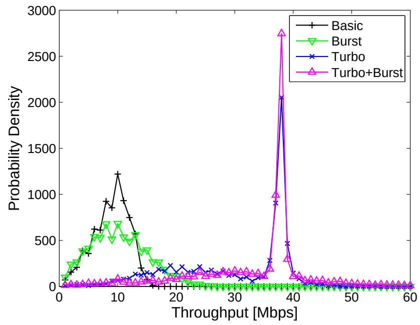
(b) *Turbo+Burst Mode.*

Fig. 4. Timeplot of UDP throughput under simultaneous activation.

Figure 4 and 5 show the per-link performance when both links are simultaneously activated, i.e., we run two Iperf instances simultaneously between TLabs and HHI and capture the packets with tcpdump at the corresponding receiver interface. Both Iperf instances send at 40 Mbps, thus above the link saturation rate. Moreover, after leaving the router, each



(a) Link 3 (pdf).



(b) Link 4 (pdf).

Fig. 5. PDF of UDP throughput under simultaneous activation.

AP has its own queue, so that it is guaranteed that the links are permanently saturated. Figures 4(a) shows the per-link throughput in basic mode when the links are set to orthogonal frequencies (link 3 to channel 6, link 4 to channel 13), and 4(b) shows the throughput with Turbo- and Burst Mode enabled (with Turbo Mode, both links are automatically set to channel 6). We see two main differences. First, in basic mode, the links can be enabled simultaneously, e.g. between 64 and 66 sec. However, we can see the effect of the interference: when one link reaches 6 Mbps, the other link goes down. This behavior is visible throughout the trace. In contrast, by enabling the two modes, the situation that both links are active only occurs for a short time. Second, the throughput in the basic mode increases slowly, e.g. link 1 increases from 0 Mbps at 64 sec to 12 Mbps at 68 sec. In contrast, with both modes (and also just with *Burst Mode*), the ramp up is reduced to less than 1 sec.

Figures 5(a) and 5(b) show the throughput distribution of link 3 and 4 respectively. Interesting is that both links maintain their dominant peak at 36 Mbps when both modes are enabled, but a non-negligible part of the samples is distributed over lower throughput values. Therefore (see first two lines of Tables III(c)), the average throughput reaches 23.1 and 22.8 Mbps, compared to 8.4 and 6.2 Mbps in the basic mode. Eventually, we look at the aggregated throughput over the twin links, as they can be seen as one bigger link at a higher level, we measured an average throughput of 14.6 in the basic mode that increases to 45.8 Mbps when both modes are enabled - a gain by a factor of 3.

Next, we repeated the tests with TCP instead of UDP. The mean throughput, the RTT and the percentage of retransmitted packets are reported in Tables III(c) and III(d) respectively. The throughput does not degrade from the UDP measurements. The percentage of retransmitted packets is around 0.2%. Thus, the TCP throughput does not suffer even though the links are activated alternatively when *Turbo Mode* is enabled and in spite of the short RTTs.

Finally, we can compare these results with the single link activation results from Section III-A and Section III-B to discuss the question whether it pays off to build twin links to enhance the link capacity. Looking at the results obtained with basic mode in Table III(a), we can see that the total UDP throughput when both links are enabled ($14.6 = 8.4 + 6.2$ $Mbps$) is exactly the sum of the throughput obtained when each link is independently activated ($14.6 = 8.4 + 6.2$ $Mbps$). If we enable the *Burst mode*, the total throughput when both links are active ($19.9 = 13.0 + 6.9$ $Mbps$) is lower that the sum of the individual throughput from Table III(a) ($27.0 = 14.2 + 12.8$ $Mbps$) but higher than individual link throughput. In contrast to the normal, *Burst mode* increases the transmission rate and, consequently, the probability of having interference. When we enable also the *Turbo mode*, the sum of the throughput we obtain ($45.9 = 22.8 + 23.1$ $Mbps$) is lower than the throughput of each of the two links obtained in the previous tests (50.3 and 51.2 $Mpbs$).

Concluding, in order to achieve higher throughput, it is better to use just one link with *Turbo mode* enabled. The channel of a single link is sufficiently stable to support a high data rate (Figure 2(a)). The antennas are not sufficiently separated, therefore the link transmissions cause high mutual interference (mainly at receiving side). When *Turbo mode* is not available, two parallel links (operating at orthogonal channels) can almost double the throughput and can therefore be used to increase the network capacity. However, these considerations apply only for the $2.4GHz$ band in which only one channel is available for the *Turbo mode*. In our ongoing work, we are evaluating the use of parallel links both with *Turbo mode* enabled operating on orthogonal channels in the 5 GHz band.

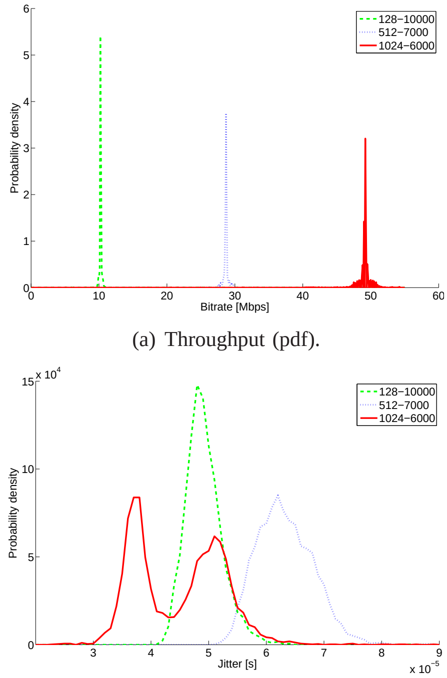
Finally, here we have provided evidences on how two parallel links - when correctly configured - can be efficiently used to adopt load balancing techniques, redundancy policies, and multi-path transmissions.

IV. Application Traffic Measurements

To study the impact of the network traffic over *MagNets* and to trace a reference for the performance of real applications, we designed two kind of experiments considering (i) the impact of the offered traffic load and (ii) the impact of competing and more realistic traffic (CBR and VBR multi-sources). This analysis is conducted by using D-ITG.

A. Traffic Load

According to the nominal capacity of the selected link of *MagNets*, in this section we present the performance achieved under three different traffic classes (named *low*, *medium* and *high* and related to different traffic loads). The first was obtained sending UDP packets with a payload of 128 Bytes at a rate of 10000 pkt/s. Thus, injecting about 8 Mbps into the network. The *medium* traffic class was produced with 512 Bytes UDP packets sent at a rate of 7000 pkt/s. This corresponds to about 20 Mbps. The last traffic class we used, *high*, was obtained sending 1024 Bytes UDP packets at a rate of 6000 pkt/s. This implies that about 50 Mbps were injected into the network. This permits to study the behavior of the wireless link under its three main conditions: far from the saturation, close to the saturation, in saturation. In Figure 6(a) the PDFs of throughput samples, collected with a period of 50 ms, are sketched for the three traffic conditions. As a first consideration, *MagNets* is able to transport nearly all the packets we generated. The average packet loss ranges from 0.15% (*high* traffic load) to 0.3% (*low* traffic load). We can also note how the PDFs become broader as the throughput increases (i.e. the packet rate decreases). Important, this means that *MagNets* is affected more by the bit rate and packet size than by the packet rate.



(a) Throughput (pdf).

(b) Jitter (pdf).

Fig. 6. Impact of different traffic loads.

Figure 6(b) shows the PDFs of the jitter achieved with these three traffic loads. Also for this parameter, the distributions become broader as the throughput increases. Also, the *high* traffic load presents a bimodal PDF, quantifying the expected dependency of the jitter on traffic load.

B. Multi-sources

To trace a reference, the previous Section was characterized by that fact that, in every measurement interval, a single traffic

TABLE V

UDP TRAFFIC: CONCISE STATISTICS OF THE *24h* TRACE ON LINK 3.

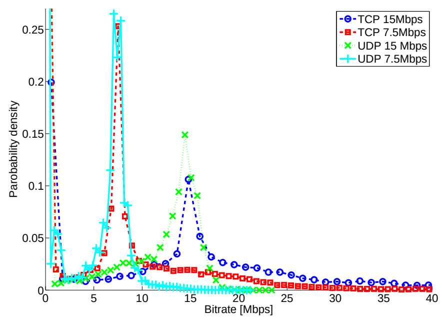
	Mean	Min	Max	Median	StDev	IQR	Entropy [bit]
Bitrate	37.23 Mbps	0.00 Mbps	45.47 Mbps	36.86 Mbps	3.36 Mbps	4.18 Mbps	5.10
Bitrate day	36.85 Mbps	0.00 Mbps	44.24 Mbps	36.78 Mbps	3.61 Mbps	4.26 Mbps	4.95
Bitrate night	37.90 Mbps	0.25 Mbps	45.47 Mbps	37.19 Mbps	2.73 Mbps	4.10 Mbps	4.55
Jitter	1.96e-005 s	0.00e+000 s	5.08e-003 s	1.50e-005 s	3.67e-005 s	1.00e-005 s	3.64
Jitter day	2.17e-005 s	0.00e+000 s	5.08e-003 s	1.60e-005 s	3.86e-005 s	1.30e-005 s	3.56
Jitter night	1.59e-005 s	4.00e-006 s	2.91e-003 s	1.40e-005 s	3.29e-005 s	8.00e-006 s	2.85
Packet loss	910 pps	0 pps	10000 pps	980 pps	902 pps	1060 pps	4.67
Packet loss day	1004 pps	0 pps	10000 pps	1020 pps	992 pps	1060 pps	4.54
Packet loss night	745 pps	0 pps	10000 pps	920 pps	687 pps	1020 pps	4.15
Delay	1.78e-002 s	0.00e+000 s	2.88e-001 s	1.57e-002 s	1.28e-002 s	8.03e-003 s	4.60
Delay day	1.75e-002 s	0.00e+000 s	2.88e-001 s	1.54e-002 s	1.26e-002 s	7.57e-003 s	4.37
Delay night	1.84e-002 s	0.00e+000 s	2.16e-001 s	1.63e-002 s	1.32e-002 s	8.72e-003 s	4.23

flow was present in the network (every cause of interference with other flows was intentionally avoided). This means that the presented results can be considered as an upper bound for the performance achieved by a single flow in the network. Internet traffic is - of course - very different. Normally, several traffic flows are concurrently traversing the network. In this Section, a different kind of analysis is presented. The results, we discuss here, are related to measurements performed with a varying number of concurrent traffic flows. In particular, we first present results related to traffic generated with 4 CBR concurrent TCP/UDP flows and than with 12 concurrent VBR flows.

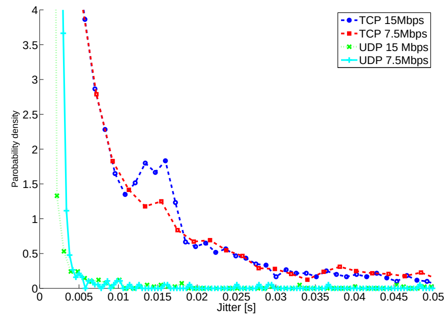
1) CBR flows: this analysis allows to evaluate the behavior of concurrent TCP and UDP flows. For this aim we generated 4 concurrent traffic flows: 2 TCP and 2 UDP flows. For both protocols, two different throughput were adopted, that are, 15 Mbps and 7.5 Mbps. The 15 Mbps flows were obtained sending 512 Byte packets at a rate of 3667 pkt/s while the 7.5 Mbps flows were produced sending packets of the same size (512 Byte) at half rate (1833 pkt/s). The total throughput we injected into the network is about 60 Mbps which causes *MagNets* to be in saturation status. Therefore, this analysis allows to observe the behavior of different flows with different protocols in such a scenario. Figure 7(a) and 7(b) depict respectively the PDFs of throughput and jitter samples.

Figure 7(a) shows that TCP flows present an heavy upper tail caused by the packet retransmissions. Such mechanism allows TCP flows to sustain, in average, the imposed throughput causing a maximum throughput of about 56 Mbps (greater than the imposed average values, 7.5 Mbps and 15 Mbps). This could have a severe impact on policy mechanisms applied to the network (e.g. shaping). Also, TCP retransmissions cause throughput samples to have higher entropy. All these considerations are not true for UDP which PDFs decay more rapidly to 0. UDP flows react to the congestion loosing packets and, therefore, their throughput is lower than the imposed value. Figure 7(b) shows the PDFs of jitter samples. TCP distribution decays slower than UDP. This causes higher mean, median, standard deviation, and IQR values compared to UDP values.

2) VBR flows: this analysis aims to assess the behavior of the traffic of real applications. In particular, we performed



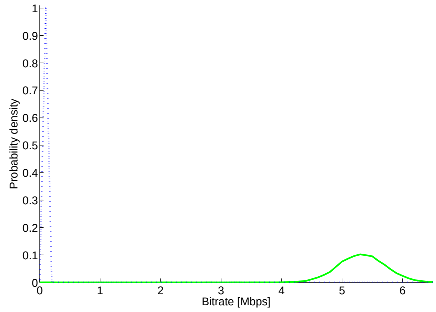
(a) Throughput (pdf).



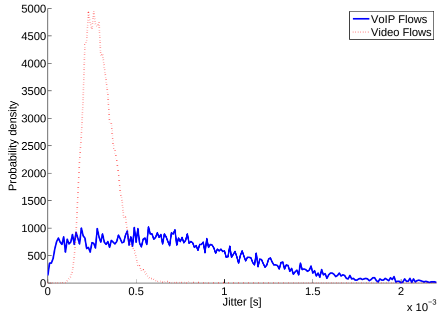
(b) Jitter (pdf).

Fig. 7. Impact of CBR multi-sources.

20 measurements of 2 minutes. During each measurement, 12 concurrent flows were injected in the network. The first 8 flows are representative of UDP video streaming traffic. According to model proposed in [18], they were generated with a constant IDT ($24 frames/s * 30 pkt/frame = 720$ pkt/s) and a Normal PS ($\mu = 926.4 Bytes$ and $\sigma = 289.5 Bytes$). The remaining 4 flows are representative of CBR VoIP traffic flows codified using ITU G.711.1 codec. This kind of traffic was characterized by a PS equal to $92 Bytes$ ($80 Bytes$ of RTP payload plus $12 Bytes$ of RTP header) and an IDT equal to $100 Pkt/s$. The average total throughput we injected is equal to about 45 Mbps. For this reason the *MagNets* link was close to saturation status. Figure 8(a) and Figure 8(b) show the PDF of the throughput and of the jitter of the two types of traffic. Considering that the total generated traffic is about 45 Mbps, we can state that *MagNets* provides very satisfying



(a) Throughput (pdf).



(b) Jitter (pdf).

Fig. 8. Impact of VBR multi-sources.

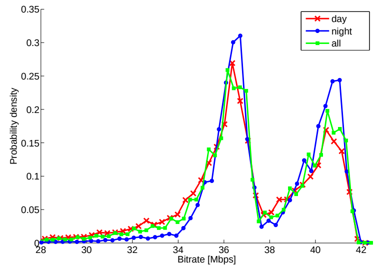
results. Interesting, *MagNets* is able to accurately transport all the sent packets. Also, the average jitter of the VoIP flows is 7.21 ms. This means that, according to the values reported in [7], the *MagNets* link is able to carry real time traffic at very high bit rates. The compliance with [7] is also confirmed by the statistics of the packet loss samples. The average packet loss is indeed 0.58 and 0.08 pkt/s for Video and VoIP flows respectively. Which means, in percentage terms, about 0.08% for the both kinds of traffic.

V. Impact of Environmental Factors

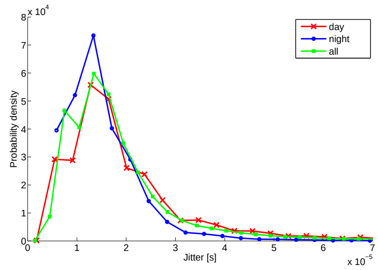
A. Day Time Impact

The measurements in this and previous papers are just single snapshots of the backbone conditions. However, we ignore how the performance of *MagNets* varies over longer time scales, e.g. between day and night or due to special environmental influences. To assess the impact, we performed a *24h* measurement. On link 3 we measured the application-level throughput, delay, jitter and packet loss in 33 measurements performed every 45 minutes and using D-ITG. In each measurement, UDP traffic was injected for 120 sec at a rate of 10000 pkt/s with a payload of 512 Bytes, i.e. at rate of 41 Mbps. The resulting traces are sampled at 50 ms.

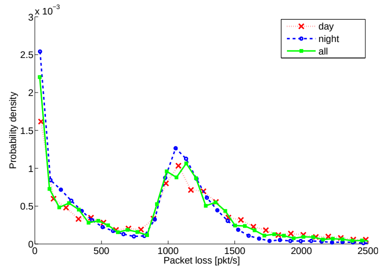
To assess the day time impact, we define measurements between 7:45 a.m. to 9:15 p.m as *day* and the rest as *night*. Figure 9 shows the resulting throughput, jitter, packet loss, and delay distributions, some related statistics are reported in Table V. Besides the mean, medium, maximum, minimum and stdev, we also report the inter quantile range (IQR) values and the *Entropy*. The IQR is the difference between the $75th$ and $25th$ percentiles. Together with the mean, IQR provide better insight that averages for skewed distributions. The *Entropy*, defined as the *information content*, measured in bits, of the samples quantifies the randomness of the considered parameters.



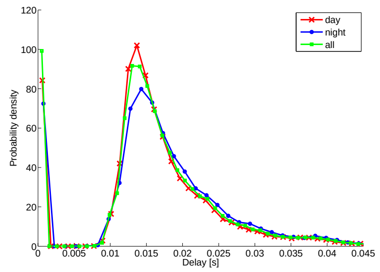
(a) Throughput (pdf).



(b) Jitter (pdf).



(c) Packet loss (pdf).



(d) Delay (pdf).

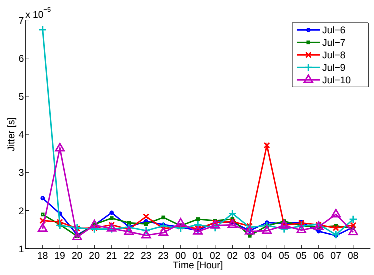
Fig. 9. Day time impact on UDP Traffic on link 3.

The throughput shows a bi-modal distributions for both day and night times. This is likely due to the rate adaptation algorithm implemented by the APs. Samples collected in the *day* hours are more spread around their median value (36.78 Mbps). This implies a higher standard deviation value (3.61 Mbps). In contrast, the median of the night samples is 37.19 Mbps with a stdev of 2.73 Mbps only. The entropy of the *day* samples (4.95 bit) is higher than the *night* samples (4.55 bit).

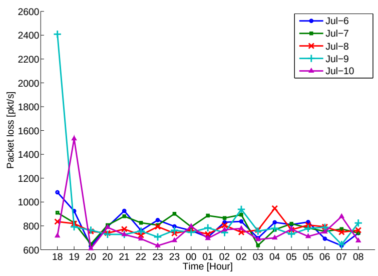
Similar considerations apply for the jitter, packet loss and delay. Samples collected during *night* have a smaller mean, stdev and less entropy. All these differences are likely due to the lower degree of interference. However, the differences are far below 1%. Thus , we conclude that the *MagNets* links are not influenced by day and night effects.

B. *Impact of Environment/Events: the 2006 FIFA World Cup*

Finally, we study the impact of special social events, as experienced in Berlin during the 2006 FIFA World Cup. During the games, up to a million people gathered in the streets near the backbone location, and a large part of the 3.3 million inhabitants of Berlin were watching the game on TV. Do these non-technical variables change the interference patterns or have other effects that may impact the backbone performance?



(a) Jitter (timeplot).



(b) Packet loss (timeplot).

Fig. 10. Impact of 2006 FIFA World Cup on UDP traffic on link 3.

To assess the impact, we performed a set of 14h long measurements during 5 days on link 3. 18 measurements lasting 2 minutes each were performed with the same parameters described above. On July 9, the championship final was played in Berlin's Olympiastadion. On July 8, the game was played in Munich, but since the German team played, similar conditions can be expected. As baselines, we measured the parameters on July 6, 7 and 10.

Figures 10(a) and 10(b) show the jitter and packet loss as a function of the day time for the 5 different days. The results show that the links are more stable on July 8, 9 from 21:00 to 23:00, i.e. during the matches. But also on July 10, the link seemed stable. Moreover, the differences are not significantly large such that we conclude that the environmental conditions have a negligible effect on the backbone performance.

VI. Related Work

MagNets is just one of many emerging wireless networks, including next generation wireless networks [17] and MANET testbeds [13]. Our prior work showed that the *MagNets* testbed features a set of unique characteristics and a challenging set of parameters, and presented a basic link characterization [8], [9]. This work, in contrast, is the first work to study the WiFi performance under high speed conditions and varying a large set of operating parameters. Related backbones, such as the *Digital Gangetic Plains (DGP)* [2] [16] in India also uses directional antennas, but the throughput is limited to a few Mbps due to the large link distance of several km. Similarly to [5], we perform a deep experimental analysis. However, our work considers, besides the throughput, other application layer performance indicators such as packet loss, jitter and round trip time. Similarly, the TfA network in Houston, Texas [4] and the MIT roofnet [3] contain directional antennas, but their throughput is also limited to single-digit throughputs. Moreover, differently from [3], we investigate also aspects like the performance of concurrent flows and the change of performance over time. Differently from [4], we consider also packet loss, jitter, round trip time, TCP retransmission as performance indicators and VoIP- and VoD-like probing traffic. Moreover, the related networks do not closely study the impact of interference created by private and company hot spots and other dense urban area influences. Finally, the *MagNets* high-speed backbone with its directional antennas contrasts the WiFi mesh networks using omni-directional antennas deployed in cities as well as research networks such as the *MIT roofnet*.

VII. Discussion and Conclusions

The objective of this paper was to evaluate a wireless backbone deployed in the city of Berlin to assess whether and to what degree high-speed communication over wireless access networks are possible. The backbone was designed towards this objective, e.g. by deploying directional antennas or by building nodes that allow concurrent transmissions over different links. The results show that high-speed wireless backbones are feasible, as we measured up to 62 Mbps application-layer throughputs with off-the-shelf 802.11 Super-A/G hardware. The throughput was also sustained over multiple hops, being limited by low transmission rates. Our results therefore significantly differ from the dismal throughput of recent mesh networks that use omnidirectional antennas and do not allow for concurrent transmissions because each AP only has one WiFi card. As hardware is increasingly available with at least 2 WiFi cards and possibly paired with MIMO or sector antennas, we expect that wireless networks will make a giant step towards the vision of an ubiquitous high-speed Internet access.

Our results show a wide diversity in link characteristics. The dominant source of throughput degradations and fluctuations is interference - in spite of the use of directional antennas - whereas sources such as day and night variations or environmental events have a negligible impact on the backbone. In a dense urban area, the $2.4GHz$ spectrum is used heavily shared and does no longer allow for an efficient usage. At the moment, interference is low in the $5GHz$ range and therefore the throughput is significantly higher, but we have to be aware that APs with multiple WiFi cards will quickly use up the spectrum.

We hope that the measured link characteristics find their way into the networking community. As outlined in the GENI [**?**] design documents, experimental measurements are the drivers to design or adjust network protocols and the input for simulation scenarios. Of course, unlike in wired environments where links have a given capacity, wireless measurement studies are extremely sensitive to the environment and are thus unique. Nevertheless, or exactly for this reason, we hope that the networking community will move away from using simulations that assume rates of single-digit physical layer transmission rates and instead use both standard low rates *and* the high rates obtained from the *MagNets* backbone.

While our work has been able to shed light onto the potential of wireless communication, we are still far away from understanding the backbone. While we have been able to use tools and techniques from the wired network world, we are still facing a number of problems that need to be resolved in the future. For example, the fact that our APs use a proprietary OS prevents us currently from even trying to understand why resources change the way we measured them. We acknowledge the work of the open source community to provide access to lower layer information. This information would allow us to correlate application-layer performance with lower-layer information. Moreover, it is vital that more tools are being developed to automatize measurements at different levels. In particular, for wireless measurements, these tools must gather and combine information sources from different layer and correlate them. Only then can we get a fundamental understanding of how wireless technology can and will revolutionize the society's perception of the Internet.

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