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Interference Measurements in an 802.11n Wireless Mesh Network Testbed

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***Abstract*—Interference measurements in an infrastructure 802.11n *Wireless Mesh Network (WMN)* testbed are described. Each wireless router consists of a Linux processor with multiple dual-band 802.11a/b/g/n transceivers. The 5 GHz band can be used for backhauling, and the 2.4 GHz band can be used for end-user service. The backhaul links use sectorized 3x3 MIMO directional antenna, to support directional parallel transmission over orthogonal channels. A Linux-based device driver has been modified to adjust the physical layer parameters. Each 802.11n transceiver can be programmed to transmit over a 20 MHz spectrum without channel bonding, or a 40 MHz spectrum with channel bonding. The 802.11n standard supports up to three orthogonal channels, 1, 6, and 11. The routers can be programmed to implement any static mesh binary tree topology by assigning *Orthogonal Frequency Division Multiplexing* (OFDM) channels to network edges. The routers can be programmed to implement any general mesh communication topology by using a *Time Division Multiple Access* (TDMA) frame schedule, and assigning OFDM channels to network edges within each TDMA time-slot. Measurements of co-channel interference, the *Signal to Interference and Noise* (SINR) ratio and TCP/UDP throughput for the 802.11n network testbed are presented. It is shown that maximizing TCP/UDP throughput in 802.11n networks can be challenging, even with very high SINR (30-40 dB) links, MIMO directional antenna, and frame aggregation with block acknowledgements. In order to maximize bandwidth efficiency, the highest quality (and cost) MIMO directional antenna appear to be necessary, and it is unlikely that mobile users can use such antennas. Our interference measurements can be used to optimize the performance of large WMNs using 802.11n technology.**

***Index Terms*—wireless mesh network; 802.11n; co-channel interference; noise; SINR; TCP throughput; TDMA, OFDM**

I. INTRODUCTION

Multihop infrastructure wireless mesh networks (WMNs) as shown in Fig. 1 represent a low-cost wireless access technology, which can potentially provide inexpensive communication infrastructure to much of the world. Industry estimates that by 2020 there will be several billion wireless devices, and that the majority of the Future Internet traffic will be due to wireless devices. Capacity and scalability are key challenges for such wireless access networks. In principle, multichannel wireless mesh networks can use multiple radio channels in multiple spectrum bands to improve system capacity. For example, spectrum in the 5 GHz band can implement the backhauling of traffic between the stationary wireless routers in Fig. 1, and spectrum in the 2.4 GHz band can implement the communications between the routers and mobile end-users.

Statistics on physical layer noise and co-channel interference in such WMNs are necessary for design optimization.

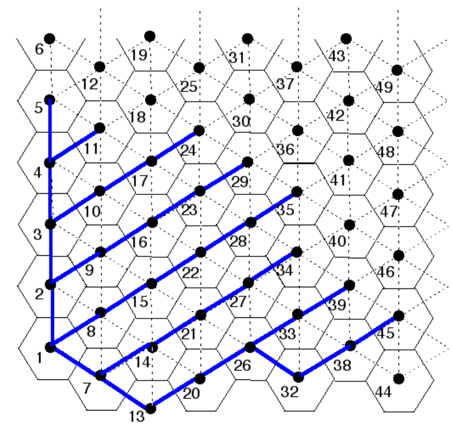


Fig. 1. A Wireless Mesh Network of 802.11n wireless routers supporting a backhaul tree (bold edges).

Several papers have described the development of 802.11a/b/g testbeds using older off-the-shelf technologies [1,2]. However, few papers have described 802.11n testbeds, since the technology is relatively new and stable open-source device drivers have only been made available recently. (Manufacturers do not release their 802.11b device drivers, and open-source device drivers for the Linux OS are written and tested by volunteers in the open-source community.) As a result, there have been relatively few published measurements for the SINR ratios and co-channel interference encountered in 802.11n WMN testbeds using MIMO directional antenna. There have also been relatively few published results on the actual TCP/UDP throughputs achieved over 802.11n testbeds.

To address these problems, a 802.11n WMN testbed called the *Next-Generation 2 (NG2) Mesh* has been developed using the latest commercially-available technologies and the latest stable open-source device drivers. Each node consists of multiple dual-band IEEE 802.11a/b/g/n transceivers and 3x3 MIMO directional antenna. Detailed measurements for the *Received Signal Strength Indicator* (RSSI), SINR, co-channel interference and achievable TCP/UDP throughputs are reported, which can be used to optimize system designs.

The IEEE has specified standards for spectral transmission masks in 802.11 standard [3]. Fig. 2 illustrates the 11 channels in the 802.11 WiFi standard in the 2.4 GHz band. The channels are spaced 5 MHz apart. Transmission on any channel requires $\approx$ 20 MHz of spectrum, and as a result there is considerable

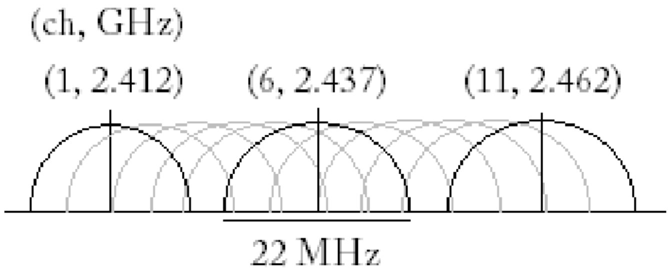


Fig. 2. The IEEE channel map.

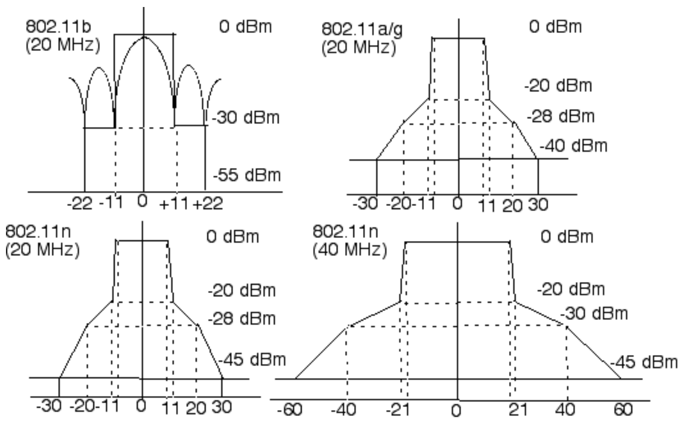


Fig. 3. 802.11 spectral masks.

interference between adjacent channels, as shown in Fig. 2. Channels 1, 6 and 11 are logically orthogonal, i.e., their 20 MHz spectrums are non-overlapping.

The IEEE 802.11a/b/g/n spectral masks are shown in Fig. 3. According to the IEEE standard [3], a 20 MHz 802.11a/g transmission should have a 0 dBm bandwidth over a range of 18 MHz, with -20 dBm at 11 MHz frequency offset, with -28 dBm at 20 MHz frequency offset (4 channels away), and reach the maximum reduction of -40 dBm at $\geq$ 30 MHz frequency offset (6 channels away). According to the IEEE standard, a 20 MHz 802.11n transmission should have a 0 dBm bandwidth over a range of 18 MHz, with -20 dBm at 11 MHz frequency offset, with -28 dBm at 20 MHz frequency offset, and reach the maximum reduction of -45 dBm at $\geq$ 30 MHz frequency offset.

802.11n also allows *Channel-Bonding*, where two 20 MHz channels are used for transmission. According to the IEEE standard, a 40 MHz 802.11n transmission should have a 0 dBm bandwidth over a range of 38 MHz, with -20 dBm at 21 MHz frequency offset, with -28 dBm at 40 MHz frequency offset (8 channels away), and reach the maximum reduction of -45 dBm at $\geq$ 60 MHz frequency offset (10 channels away).

The spectral mask requirement ensures adequate signal attenuation between 802.11 transmissions. However, the spectral mask requirements apply to a single device tested in isolation. Interference from other devices operating in the same bands (i.e., microwave ovens) will add interference, which cannot be controlled.

Our 802.11n testbded was developed, following our earlier work of developing an 802.11a/b/g testbed [14]. In order to test the TCP/UDP throughput, co-channel interference, RSSI and SINRs in a practical 802.11n network deployment, large TCP and UDP file transfers were performed over each channel in the NG2 Mesh testbed, and the achievable TCP throughput and interference on the other 10 WiFi channels was measured. To summarize our results: The transmission power was set at 17 dBm over a very short (5 meter) and perfectly unobstructed *Line-of-Sight* (LOS) wireless link. The 802.11n transmissions were $\approx$ 20 MHz wide. The *Automatic Rate Adaptation* mode was used, so the transceivers selected their *Modulation and Coding Scheme* (MCS) index and transmission rate automatically, based upon the current channel condition. In our high-SINR environment, the transceivers selected the setting MCS(15), with 2 distinct spatial streams for transmission. (802.11n supports between 2 and 4 distinct spatial streams over the same 20 MHz channel.) The MCS(15) setting is suitable for wireless links with very high SINRs. It uses a 64-QAM modulation scheme, 2 distinct spatial streams, with a 5/6 rate forward error correction (FEC) code, a PHY layer transmission rate of 144 Mbps, with a *Short Guard Interval* of 400 nanosec between packets. Frame aggregation was used, to achieve larger PHY layer packets with reduced protocol overhead. (802.11n supports 2 frame aggregation schemes, the *Aggregated Mac Service Data Unit* (A-MSDU) and the *Aggregated Mac Protocol Data Unit* (A-MPDU). The A-MSDU scheme increases packet size from $\approx$ 2 Kbytes to $\approx$ 8 Kbytes, and A-MPDU allows for very large packets up to 64K bytes.) In our tests, after frame aggregation each packet includes $\approx$ 5 Kbytes of data payload, plus the TCP/IP overhead (approx. 20 bytes), the PLCP overhead (approx. 24 bytes), and the MAC-layer overhead (approx. 28 bytes).

During our tests, very high SINRs in the range of 35...39 dB were consistently measured. We observed that the wireless link quality was largely static with no noticeable changes over any 24 hour period, except for changes in activity in remote 802.11 networks. The measured TCP throughput was 47.85 Mbps, much lower than the PHY transmission rate of 144 Mbps, indicating that the protocol overhead is significant, even with short-distance unobstructed links with very high SINRs, using frame aggregation and block acknowledgement. We observed PERs in the range of 1-5%. In a large deployment these SINRs are typically reduced by the distance cubed, so a real 802.11n deployment should have lower SINRs.

The research community has recognized that 802.11 protocol overheads, such as interframe spacings, guard intervals, PHY layer headers (including a preamble and PLCP), the channel contention process and acknowledgement all will reduce usable throughput. A few researchers have shown that UDP throughputs are degraded over longer (i.e., 1 kilometer) links, due to SINR degradation. Our tests indicates that the TCP throughput reduction can be quite significant, even over very short (5 meters) and perfectly unobstructed links with very high SINRs, using frame aggregation and block acknowledgement. Even over such high-SINR links, our 802.11n TCP throughput is $\approx$ 33% of the PHY layer transmission rate. Using higher levels of frame aggregation should not help much, since larger packets are less likely to be achieved without errors. We identify the causes and suggest several avenues to address these issues in the conclusions. Given the lack of published data on co-channel interference, SINRs, and achievable TCP/UDP throughputs in realistic 802.11n network testbeds (without expensive narrow-beam mounted MIMO antennas), our data should help optimize network designs.

Section 2 summarizes other recent wireless networking testbeds that report physical layer metrics. Section 3 describes the design of the NG2-Mesh. Section 4 presents the physical layer measurements of NG2-Mesh. Section 5 closes with our conclusion and future work.

II. Related Work

References [1,2] summarize some recent mesh testbeds using the older 802.11a/b/g technology. Reference [4] reports on wireless link performance between outdoor 802.11n nodes placed 800 meters to 2 kilometers apart. Expensive narrow-beam MIMO directional antennas mounted on towers were used in a radio-silent and line-of-sight (i.e., LOS) setting. They tested UDP throughputs over a 148 Mbps PHY layer link, and observed 100 Mbps on 300m links and 40 Mbps on 800m links respectively, for efficiencies of 66% and 27%. They attributed the UDP throughput reduction on long links to lower SINRs. They did not explore the TCP or UDP performance on short-distance very-high SINR links.

Reference [5] reports that in a densely populated apartment complex with numerous uncoordinated wireless networks, 802.11n performance was severely degraded especially for TCP transmissions, due to the activation of back-off mechanisms (i.e., CSMA/CA) in the presence of nearby interference.

In [6], several causes of interference were identified in nearby IEEE 802.11n multi-band wireless links. Signal leakage leading to *Out-Of-Band* (i.e., OOB) interference resulted from filter imperfections in the transceivers, which can trigger back-off mechanisms when using TCP. This situation prevents multiple parallel transmissions and therefore degrades overall system throughput. They report that a robust solution to this problem is to use highly-directional antennas to restrict OOB interference, i.e., the LairdTechnology S245112PT narrow-beam point-to-point directional MIMO antenna. In [7], several causes of interference were also identified in nearby IEEE 802.11n multi-band wireless links. They observed that OOB interference can reduce the number of useable orthogonal channels, from 3 down to 1, in the 2.4 GHz band. However, they used an omni-directional antenna and their results will not apply when highly directional antenna are used. They observed that the links can perform adequately if the omni-directional antennas at one node are spaced apart, and if power control is implemented to decrease unnecessary OOB interference.

III. NG2 MESH Testbed Architecture

Our test-bed is composed of commercially available 802.11n components. Table I summarizes all software and hardware used The overall physical setup of each network node type is depicted in Fig. 4. Each network interface card (i.e., NIC) connects to a laptop running BackTrack Linux where all network node configurations are made. For backhauling traffic, the NICs of the mesh routers are connected to a Laird Technolgies 3x3 sectorized MIMO directional antenna array, while end-user stations are attached to a Laird Technologies omni-directional antenna.

TABLE I
Test-bed Components

Component	Specifications
Laptop Type 1	Intel Q9300 2.53GHz CPU, 4GB RAM, 8GB HDD
Laptop Type 2	Intel L620 2.00GHz CPU, 4GB RAM, 8GB HDD
OS	Linux 64-bit BackTrack 5, kernel 2.6.38
Wireless Interfaces	AR9380 3x3 chip-set, ath9k driver
Spectrum Analyzer	Wi-Spy 2.4i, Chanalyzer Lite & Kismet Software
Antenna Type 1	Laird S24517PT directional sector 3x3 MIMO
Antenna Type 2	Laird SM24513PUFL omni-directional 3x3 MIMO

In an infrastructure multichannel Wireless Mesh Network (WMN), the backhaul traffic can be provisioned using TDMA scheduling. The edges between adjacent stationary wireless routers occur on stationary high-capacity *Line-of-Sight* (LOS) paths. These stationary LOS paths are not subjected to the rapid fading associated with fast-moving mobile devices. The stationary LOS paths may experience slow fading due to weather changes, occurring over time-scales of many minutes or hours. The time-axis can be divided into TDMA scheduling frames, each consisting of several (i.e., 1,024) time-slots. Each time-slot is sufficient to transmit a backhaul packet between neighboring stationary wireless routers. The data-rate of each edge can be controlled by selecting the 802.11n *Modulation and Coding Scheme* (MCS) index. Each spatial stream has 8 MCS settings labelled MCS(0)...MCS(7), and a transmission can use up to 2 spatial streams in our network. MCS(0) is suitable for low SINRs (BPSK modulation,1/2 rate coding, PHY data-rate of 7.2 Mbps with short guard intervals of 400 ns). MCS(7) is suitable for high SINRs (64-QAM modulation, 5/6 rate coding, PHY data-rate of 72 Mbps with short guard intervals). In 802.11n devices, the MCS index can be configured from the device driver when *Automatic Rate Adaptation* is disabled. The data-rate of each edge is fixed during a TDMA scheduling frame, and can be updated in subsequent TDMA scheduling frames when the environment (i.e., weather) changes. The duration of a TDMA scheduling frame may vary, with a nominal duration of several seconds. Assume a modest MCS index 5 (64-QAM, 2/3 rate coding, 57.8 Mbps PHY data-rate with short guard intervals) per spatial stream. Assuming nominally-sized 64 Kbyte packets for backhauling with 2 spatial streams, each time-slot has a duration of $\approx$ 4.5 milliseconds. Assuming 1K time-slots per scheduling frame, the scheduling frame has a duration of $\approx$ 4.6 seconds. In this TDMA mesh configration, the wireless routers may be required to change channels every 4.5 millisec, corresponding to a rate of $\approx$ 220 Hz. (The current 802.11n chipsets support rates of 1 KHz.) TDMA

Fig. 4. WMN node configurations.

link scheduling will select different subsets of conflict-free edges to transmit or receive concurrently in each TDMA time-slot over orthogonal channels. In an infrastructure WMN, the traffic between wireless routers and *mobile end-users* can be provisioned using *Opportunistic Scheduling*. This traffic does not use TDMA scheduling, since the uplink / downlink channels between a stationary wireless router and *mobile end-users* typically experience fast-fading, where the channel conditions may change rapidly in time. Opportunistic schedulers typically monitor the long-term and instantaneous channel states, and select packets for transmission to mobile end-users considering the queue backlog, the current channel state, the long-term channel state, and other factors.

In our test-bed, two active nodes were spaced 5 meters apart and were configured to operate in infrastructure mode. Most tests were conducted without Channel-Bonding, i.e., using 20 MHz transmissions (called HT20 transmissions). Large TCP file transfers were initiated between the two active mesh nodes (a sender and receiver, to eliminate local channel contention), over high-SINR unobstructed and fixed LOS paths. During these transmission tests, statistics were captured internally at sender/receiver nodes via the device driver debug log. Additional RSSI metrics were captured with the spectrum analyzer, which was placed beside the mesh router's antenna array.

We also performed tests of transmissions using channel-bonding using the high throughput 40 MHz transmissions, called HT40 transmissions. All network nodes were configured into the IEEE 802.11n PHY mode to transmit on up to 3 concurrent spatial streams with channel bonding. Throughput enhancements that were found to be beneficial to overall performance [4] including aggregated MAC protocol data unit (i.e., AMPDU) frame aggregation and block acknowledgement to reduce MAC layer overhead, 400 nsec short guard interval (SGI) as well as transmit and receive space time block coding (i.e., STBC), and PHY layer diversity were also enabled. With AMPDU frame aggregation, our packet sizes where $\approx$ 5.2 Kbytes.

A. The Wireless Interfaces

The Atheros (i.e., now Qualcomm) AR9380 IEEE 802.11a/b/g/n chip-set was used in all network nodes and supports operation in the dual 2.4 and 5 GHz bands. The maximum *Modulation and Coding Scheme* index 31 supports a PHY rate of 600 Mbps when using 4 spatial streams. According to the reference design specifications [8], the device supports up to 1000 channel switches per second, which indicates that TDMA-based link scheduling can achieve a channel switching rate of 1 kHz in software. A transmission power of 17 dBm was configured for all AR9380 modules in our test-bed. The C-based Atheros ath9k drivers from the compat-wireless 2.6.38.2-2 package [9] were compiled to operate all WMN nodes in our test-bed.

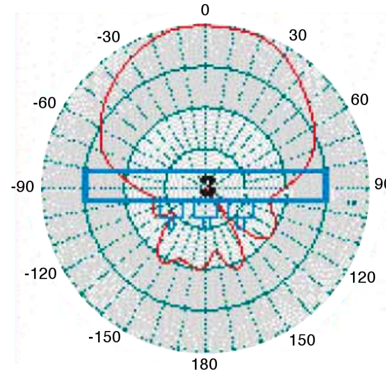


Fig. 5. 3x3 MIMO directional antenna radiation pattern.

B. The MIMO Directional Antenna

Laird MIMO antennas supporting 3x3 operation are attached to the AR9380 chip-sets. Both dual band antenna types offer antenna element polarization to provide enough path diversity to sustain up to three concurrent spatial streams [4]. The frequency range supported is (2.4...2.472) GHz and (5.18...5.825) GHz [12], [13].

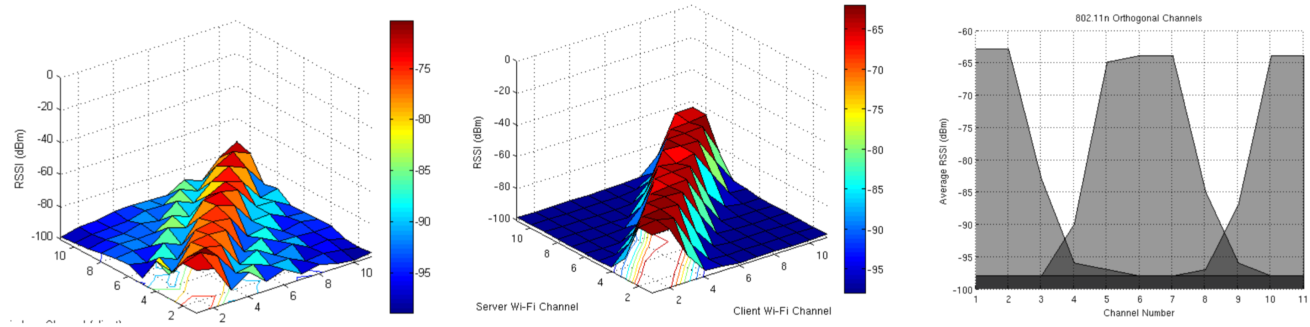
The Laird S24517PT MIMO antenna is encased in small low-profile polycarbonate radome which can be mounted vertically. The antenna provides a modest 8 dBi gain at 2.45 GHz, and 10.7 dBi gain at 5.5 GHz. It has a 3 dB Beam-Azimuth of 55 degrees at 5.5 GHz, and a 3 dB Beam-Elevation of 60 degrees at 5.5 GHz. It has 2 vertical and 1 horizontal linear polarization modes, and is rated for up to 1 W of power. A typical radiation pattern at 2.45 GHz is shown in Fig. 5. This antenna has modest cost.

C. The Spectrum Analyzer

The Wi-Spy 2.4i entry-level 2.4 GHz spectrum analyzer [10] was used to capture RSSI statistics. Specialized graphing software was downloaded from [10] and [11] and was used to generate time-series RSSI plots and to capture real-time transmit signal PSDs across the 2.4 GHz band. Under windows, the device can scan the frequency range of (2.4...2.492) GHz in 375 kHz steps and report per-second RSSI readings in the range of (-102 to 6.5) dBm in 0.5 dBm steps. Under Linux, the device can scan the frequency range of (2.4...2.483) GHz every 30 ms in 199 kHz steps.

IV. Experimental Results

All experiments were conducted in a typical one condo unit in a high-rise building. The living room space where the test-bed was situated measured approximately 5x3 meters.



(a) (b) (c) Delay

Fig. 7. (a) Mesh plot of 802.11b RSSI. (b) Mesh plot of 802.11n RSSI, (c) co-channel interference, channels 1, 6 and 11.

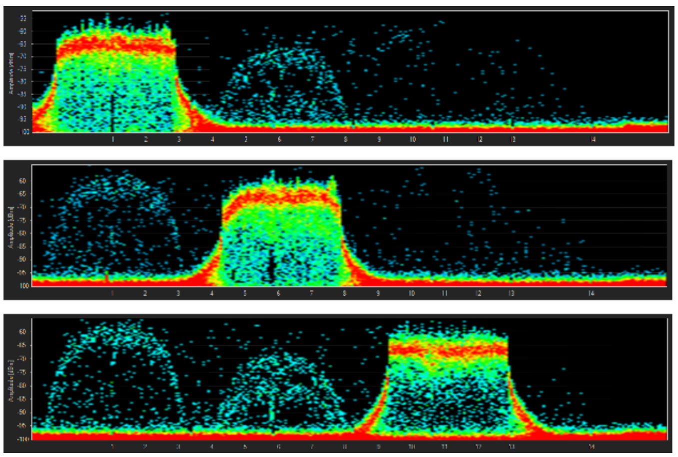


Fig. 6. Power Spectral Densities for 3 Orthogonal channels in the 802.11n 2.4 GHz band.

Fourteen IEEE 802.11 networks were detected on channels 1 (-50 dBm), 2 (-72 dBm), 4 (-84 dBm), 6 (-57 dBm), 8 (-91 dBm), 9 (-92 dBm), 10 (-81 dBm), and 11 (-82 dBm) around the test-site. The *Power Spectral Densities* (PSD) for transmissions on 3 orthogonal channels are shown in Fig. 6. The PSDs obey the IEEE 802.11 spectral masks. Next, TCP file transmissions were performed between 2 active nodes using the *Automatic Rate Adaptation* mode; MCS(15) was selected with 2 spatial streams (each stream uses the same 20 MHz spectrum, 64-QAM modulation, 5/6 rate coding, PHY tx rate of 144 Mbps with short guard interval). The measured TCP throughput rate using the HT20 mode was 47.85 Mbps, for a bandwidth efficiency of $\approx$ 33%. We also tested the bandwidth efficiency of the HT40 transmission scheme, using Channel Bonding and 40 MHz of spectrum. Using the HT40 mode, MCS(15) was also selected (2 channels, each with 2 spatial streams, each using the same 20 MHz spectrum, PHY transmission rate of 300 Mbps with short guard interval). The actual TCP throughput rate for HT40 was 63 Mbps, representing a throughput increase of $\approx$ 32% over HT20. However, the bandwidth efficiency of the HT40 scheme is $\approx$ 21%. Ironically, the bandwidth efficiency using HT40 actually drops in our tests, since the HT40 TCP throughput is less than double the HT20 TCP throughput. We present several recommendations to address these low TCP throughputs in the conclusions. The UDP throughputs were also tested and observed to be about 20% higher.

A. *RSS Analysis*

To obtain interference measurements, RSSI statistics were collected across the 2.4 GHz band using a spectrum analyzer during the TCP transfers of a 1 GB movie file. The average noise level at each channel was found to be -99 dBm, i.e., all nearby 2.4 GHz devices were relatively inactive at the time of testing. The C-based socket programs used to manage TCP transfers are from [14]. Tables 2 and 3 present the RSSI levels across the 2.4 GHz band, and the co-channel interference. Each row/column of the RSSI matrices represents the RSSI for a transmission/reception on two given channels. The boldfaced cells (diagonals) represent the active channel. The average RSSI data were measured from the spectrum analyzer plots, as shown in Fig. 6. From Fig. 6, one can clearly identify the maximum RSSI data points about the 0 dBm mark and the average (i.e., most frequent) values around the darker regions at about the -20 dBm mark. The adherence to the 802.11n spectral masks can be observed in Fig. 6. The RSSI measurements are plotted graphically in Fig. 7. From tables 2 and 3, observe the higher RSSI levels in the 802.11n over 802.11b, about 10 dBm higher. In Fig. 7 observe the better transmission signal filters in 802.11n, leading to sharper spectral masks. In summary, Fig. 6-7 and Tables 2 and 3 verify that the average RSSI levels are well within the IEEE 802.11n spectral masks.

V. Conclusion and Future Work

An 802.11n wireless mesh network testbed was developed using the latest commercially-available wireless transceivers and software. (Stable open-source Linux device drivers for 802.11n transceivers where only made available recently.) A single node design consists of multiple 802.11a/b/g/n wireless transceivers which can be individually configured. Our testbed was configured to enable one large TCP file transfer on one channel over a high-SINR unobstructed Line-of-Sight (LOS) path, and the RSSI and SINR measurements were recorded on

TABLE II
RSSI AND CO-CHANNEL INTERFERENCE FOR 802.11B (DBM)

Client / Server	ch.1	ch.2	ch.3	ch.4	ch.5	ch.6	ch.7	ch.8	ch.9	ch.10	ch.11
ch.1	**-73**	-75	-93	-85	-94	-90	-967	-94	-97	-98	-97
ch.2	-73	**-70**	-76	-90	-88	-92	-91	-97	-95	-98	-99
ch.3	-85	-78	**-75**	-77	-93	-87	-94	-91	-96	-95	-98
ch.4	-81	-92	-77	**-75**	-76	-93	-88	-94	-94	-95	-95
ch.5	-97	-87	-92	-78	**-76**	-77	-92	-89	-95	-93	-95
ch.6	-923	-95	-86	-91	-78	**-74**	-77	-90	-89	-943	-95
ch.7	-93	-92	-93	-85	-88	-75	**-73**	-76	-89	-90	-96
ch.8	-95	-93	-93	-93	-86	-90	-80	**-74**	-79	-93	-90
ch.9	-97	-95	-94	-92	-93	-85	-89	-79	**-73**	-78	-91
ch.10	-97	-96	-95	-94	-93	-92	-85	-90	-78	**-72**	-77
ch.11	-98	-96	-95	-93	-93	-93	-93	-86	-91	-81	**-75**

TABLE III
RSSI AND CO-CHANNEL INTERFERENCE FOR 802.11N (DBM)

Client / Server	ch.1	ch.2	ch.3	ch.4	ch.5	ch.6	ch.7	ch.8	ch.9	ch.10	ch.11
ch.1	**-59**	-58	-75	-94	-96	-96	-96	-96	-96	-96	-96
ch.2	-60	**-60**	-62	-80	-94	-96	-96	-96	-96	-96	-96
ch.3	-84	-60	**-60**	-60	-80	-94	-96	-96	-96	-96	-96
ch.4	-96	-82	-60	**-60**	-59	-80	-94	-96	-96	-96	-96
ch.5	-96	-96	-83	-60	**-60**	-60	-73	-94	-95	-96	-96
ch.6	-96	-96	-96	-87	-62	**-60**	-60	-80	-94	-96	-96
ch.7	-96	-96	-96	-95	-85	-61	**-60**	-61	-77	-92	-96
ch.8	-96	-96	-96	-96	-96	-83	-60	**-62**	-59	-78	-94
ch.9	-96	-96	-96	-96	-96	-95	-83	-63	**-60**	-60	-76
ch.10	-96	-96	-96	-96	-96	-96	-96	-85	-63	**-61**	-60
ch.11	-96	-96	-96	-96	-96	-96	-96	-96	-84	-60	**-60**

all other channels. Our measurements show that the devices comply with the 802.11n spectral masks for both 20 and 40 MHz transmissions. Our experiments indicate that even with very short (5 meters) and perfect unobstructed LOS paths, very high SINRs (35-40 dBm), frame aggregation and block acknowledgments, the 802.11n mode can result in poor TCP throughput, i.e., about 33% of the PHY transmission rate. We suggest several avenues to address these low TCP throughput issues. First, our lower-cost 3x3 MIMO antenna provide 8 dBi gain and a wide 3-dB beamwidth of 70 degrees (at 2.4 GHz). The use of better MIMO directional antennas (i.e., 24-30 dBi gains, with narrow 4-8 degree beamwidths) appears necessary to improve gain and SINRs, but will also cost (and weigh) considerably more. It is unlikely that mobile users can use such costly and large MIMO antennas, and their TCP/UDP throughputs will be constrained. Second, higher transmission powers may help increase SINRs, when high-quality MIMO directional antennas are used to reduce unwanted interference. However, power minimization and energy-efficiency are important design goals. Third, the 802.11n MCS settings should be carefully chosen to optimize TCP/UDP throughput, given the antennas and channel conditions. Finally, a MAC-layer standard which supports static conflict-free TDMA scheduling of links in wireless mesh networks could improvement efficiency, by removing the 802.11 protocol overhead for channel contention. Given the lack of published data on co-channel interference and achievable TCP/UDP throughputs in realistic 802.11n network testbeds, our data should help optimize network designs. In addition, our designs should enable other researchers to develop 802.11n testbeds using commercially-available technologies and open-source software.

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