Physical Layer Measurements for an 802.11 Wireless Mesh Network Testbed

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***Abstract*—Physical layer measurements for an infrastructure 802.11 Multichannel MultiBand Wireless Mesh Network testbed are described. Each wireless router node design consists of a Linux processor with multiple 802.11b/g transceivers operating in the 5 GHz band for backhauling, and multiple 802.11 transceivers in the 2.4 GHz band for end-user service. Each transceiver consists of a MAC and base-band processor (BBP) in addition to a radio. A Linux-based device driver has been modified to adjust the physical layer parameters. The 802.11 standard specifies 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 frame. Preliminary measurements of co-channel interference and the signal to interference and noise (SINR) ratio for the network testbed are presented, using omni-directional antenna and the 802.11b operation mode. This data can be used to optimize the performance of large infrastructure Wireless Mesh networks using 802.11 technology.**

***Index Terms*—wireless mesh network; 802.11; co-channel interference; noise; SINR;**

I. INTRODUCTION

Multihop infrastructure wireless mesh networks (WMNs) as shown in Fig. 1 represent a low-cost access network technology, which can potentially provide 'last-mile' accessibility to much of the world. Industry estimates that by 2020 there will be several billion wireless devices, providing a range of new services. WMNs represents a promising infrastructure for supporting these wireless devices, as well providing general communications infrastructure for homes and offices. However, capacity and scalability are key challenges for such networks. Multichannel multiband meshes can use multiple radio channels in multiple frequency bands to improve system capacity and throughput. For example, channels in the 5 GHz band can implement the mesh backhauling trees between Base-Stations (BSs) in Fig. 1, and channels in the 2.4 GHz band can implement the communications between the Base-Stations and end-users. The optimized design of such WMNs requires statistics on physical layer noise and co-channel interference. However, to date there have been very few published measurements for co-channel interference and signal-to-interference-and-noise ratios encountered in practical WMN testbeds. To address this problem, an 802.11 WMN testbed has been developed and detailed noise and interference measurements are reported.

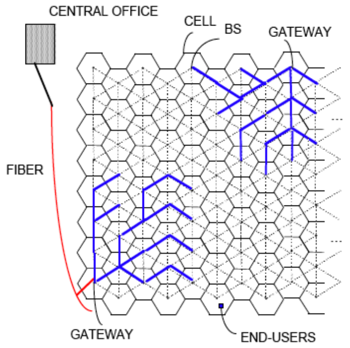
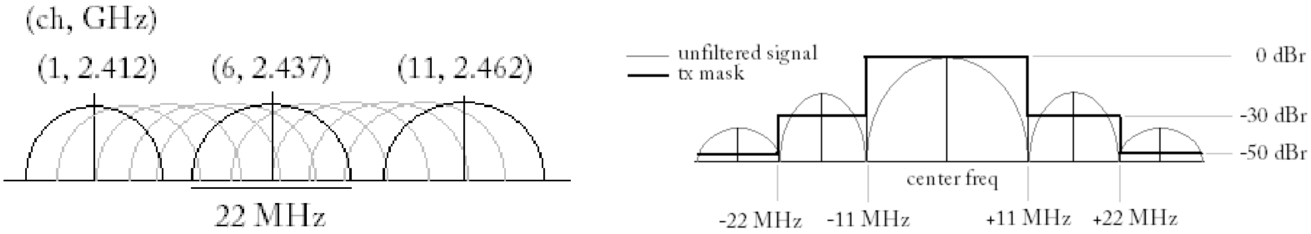


Fig. 1. A Wireless Mesh Network using a wireless cellular array.

This paper presents a small mesh testbed composed of IEEE 802.11b nodes operating in IBSS (ad-hoc) mode, called the *Next-Generation (NG) Mesh*. Each network node contains multiple wireless transceivers controlled in a Linux environment. To study co-channel interference between WiFi channels in the 2.4 GHz ISM band, preliminary physical layer (PHY) measurements for the received signal strength indicator (RSSI) and SINR are reported. The IEEE has specified standards for co-channel interference in 802.11 standard [1]. Fig. 2a illustrates the 11 channels in the 802.11 WiFi standard in the 2.4 GHz band. Each channel requires 22 MHz and channels are separated by 5 MHz. Channels 1, 6 and 11 are logically orthogonal, i.e., their spectrum is non-overlapping. The IEEE 802.11b spectral mask shown in Fig. 2b mandates a drop of at least 30 dBm at a displacement of 11 MHz (two channels) from the active channel. The standard also mandates a drop of at least 50 dBm at a displacement of 22 MHz (four channels). The spectral mask requirement ensures adequate attenuation between 802.11 channels in the ISM band. However, the spectral mask requirements apply to a single device tested in isolation, and will not apply to a real network deployment due to interference from multiple networks and other microwave devices.

In order to test the co-channel interference and SINRs in



(a) The 2.4GHz ISM Band.

(b) The IEEE 802.11b spectral mask.

Fig. 2. The IEEE channel map.

a practical 802.11 network deployment, a large file transfer was performed over one channel in the NG Mesh testbed, and the interference on the other 10 WiFi channels was measured. Using 15 dBm of transmission power over very short (5 meter) wireless links and a datarate of 11 Mbps, SINRs in that range of 20 - 30 dBm were consistently measured. In a large deployment these SINRs are typically reduced according to the distance cubed. Furthermore, 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. Given the lack of published data on SINRs in realistic network testbeds, this data may help optimize network designs.

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

II. RELATED WORK

Some other recently published wireless testbed designs that consider physical layer measurements are discussed next. Like NG-Mesh, all of them employ a Linux OS and multiple IEEE 802.11 wireless transceivers at each network node. In [2], a wireless network was installed in a natural reserve spanning several kilometers to collect ecological data. Each mesh node consists of multiple 802.11b/g wireless transceivers capable of multi-channel communication. The testbed was used to investigate the correlation between packet error rate (PER) and RSSI, to evaluate improvements in rate control algorithms and routing protocols. In [3], a campus-wide 802.11b/g WMN was used to provide internet access. Due to the close proximity of the mesh nodes, a high degree of co-channel interference was present. Although physical layer metrics such as the signal to noise ratio (SNR) were collected, no solution was proposed to mitigate the interference.

In [4], a mesh network composed of quickly deployable relay nodes was formed to target real-time emergency communication services. SNR measurements were used to infer link quality to guide the deployment of additional relay nodes. A case study concluded that SNR statistics reported by commercially available radios accurately indicate link reliability. In contrast to PER statistics, which report transmission errors that have already occurred, SNR measurements provide predictions of link failures before they occur. In [5], an 802.11a testbed was used to measure handoff latency of high-speed vehicles roaming between stationary road-side access points (APs). Handoff between APs occur whenever the link between the mobile station (MS) and the currently associated AP exhibits an RSSI that is lower than a pre-defined threshold.

In [6], a formula was derived for the amount of signal attenuation required for a small-scale network testbed to emulate a large-scale network, reflecting the different inter-node spacing. The transmit power and the inter-node spacings of the wireless interfaces were scaled down accordingly, allowing a small testbed (spanning a few meters) to emulate the large network for testing purposes. Variable attenuators (Broadwave 751-002-030 devices) were used. In contrast, the NG-Mesh testbed employs a modified Serialmonkey [7] Linux-based device in order to control the physical layer characteristics including the transmission frequency (WiFi channel) and transmission power.

In summary, while a number of 802.11 testbeds have been developed to date there are no detailed measurements of co-channel interference and SINRs in such network testbeds. In contrast to the previous testbeds, the NG-Mesh will be used to collect RSSI and SINR measurements on each channel in the ISM spectrum given an isolated file transfer on one specific WiFi channel. This data may be useful to optimize the performance of future WiFi WMN deployments.

III. THE NG-MESH ARCHITECTURE

The NG Mesh testbed was developed from commercially available WiFi components and software. Table I summarizes the system components making up a logical node in our testbed. The *product_ID:vendor_ID* codes correspond to the Linksys WUSB54G and Wi-Spy 2.4i devices.

TABLE I
TESTBED COMPONENTS

Component	**Specifications**
PC	Q9300 2.53GHz CPU, 4GB RAM, 100GB HDD
VM	VMware 7, 512MB RAM, 1CPU, 8GB HDD
OS	64-bit RHEL 5.4, kernel 2.6.18
Wireless Interfaces	13b1:000d, RT2570/RT2525E chipset, rt2x00 Driver
Spectrum Analyzer	1dd5:2400, Chanalyzer Lite / Kismet Software

A. The Testbed Configuration

As shown in Fig. 3, one node in the NG-mesh testbed consists of four Linksys WUSB54Gv4 wireless transceivers that connect to one PC via a non-attenuating four-port USB hub. The 4 wireless transceivers provide the capability to transmit or receive on $c \leq 4$ channels simultaneously. For example, each node can be configured to permanently receive on 2 arbitrary channels and transmit on one arbitrary channel. Alternatively, each node can be programmed to transmit or receive on selected channels in selected intervals of time, thereby implementing a *Time Division Multiple Access (TDMA)* style of mesh network.

To perform our experiments, the transceivers associated with one node were placed 5 meters apart. One pair of transceivers was configured to transmit a large file over a given WiFi channel using a UDP socket. Another transceiver was configured as an interference measurement device, to receive on a different WiFi channel from which RSSI and SINR measurements could be made. The transceivers in the NG-Mesh are configured to operate in ad-hoc mode with each being assigned a unique IP address and each tunable to different radio frequencies. The configuration of all network transceivers are performed via the central PC console using Linux network configuration utilities such as *iwconfig*.

The testbed can be extended in several ways. More wireless transceivers can be connected to one node, thereby enabling one node with a small footprint to emulate a larger virtual network. Alternatively, multiple NG mesh nodes can be deployed over a large geographic region.

B. The Wireless Interfaces

The Linksys WUSB54Gv4 transceiver has a retractable 2 dBi omni-directional antenna and requires no proprietary firmware. Each Linksys transceiver contains the Ralink RT2570 (MAC/BBP) and RT2525E (transceiver) chipsets. In the 2.4 GHz band, the radio is tunable between 2.412 GHz and 2.484 GHz. In the 5 GHz band, the radio is tunable between 5.180 GHz and 5.805 GHz. The allowable channel subsets are determined by the PHY mode and geographic region. The PHY modes of IEEE 802.11a, b, and g are referenced in the driver source code but by default, the PHY mode and channel are set to IEEE 802.11b and 1 respectively. The bit-rates supported by this chipset are 1, 2, 5.5, 6, 9, 11, 12, 18, 24, 36, 48, and 54 Mbps although it was found that only a maximum bit-rate of 11 Mbps was configurable in ad-hoc mode. The maximum transmission power output of this chipset is 100 mw (20 dBm). According to specifications [8], the receiver sensitivity is nominally in the range of -65 dBm to -80 dBm.

Within the Linux community, there is an active project maintained by a team of developers known as Serialmonkey who maintains and enhances open-source Linux-based device drivers for Ralink chipsets. Their legacy drivers from the May 12, 2009 build were selected to operate the wireless interfaces of NG-Mesh. All Serialmonkey [7] and Ralink driver code bases [9] are written in the C programming language.

Fig. 3. Node configuration.

The Serialmonkey legacy drivers for Ralink chipsets rely on a periodically executed code segment within a function called *CMDHandler*. By implementing a channel switching function call *AsicSwitchChannel* in software in the *CMDHandler*, a maximum frequency retuning rate of one channel switch every 30 ms was achieved. This measurement indicates that a TDMA-based WiFi network can achieve channel changes at rates of 33 Hz in software. According to the IEEE standard [1], much faster channel change times of 224 μsec can be achieved in hardware.

C. The Wi-Spy Spectrum Analyzer

Our preliminary measurements were made using an inexpensive MetaGeek Wi-Spy 2.4i entry-level ISM spectrum analyzer. The software is freely downloadable from [10] [11] for Windows, Mac, or Linux and can be used to plot real-time distributions of the energy in the ISM band. The software also computes the average and peak energies over time per frequency, and can also use a separate wireless interface to detect proximate WiFi networks. The MetaGeek Chanalyzer Lite software enables this device to scan the frequency range of 2.4 - 2.492 GHz and report the energy in the range -102 - 6.5 dBm, in 375 kHz and 0.5 dBm increments respectively, roughly once per second. Under Linux, Kismet's Spectrum-Tools software enables the device to scan the frequency range of 2.4 - 2.483 GHz and report four-hundred-and-nineteen samples every 30 ms in 199 KHz steps.

IV. EXPERIMENTAL RESULTS

A communication link was established by configuring one transceiver to transmit on the primary WiFi channel, and a second transceiver to receive on the same channel. Another transceiver was configured to receive on a secondary channel, to obtain co-channel interference measurements. The Wi-Spy spectrum analyzer was also configured to monitor the secondary channel. The transmit power of both communication endpoints were fixed at 15 dBm via device driver modifications while all file transmissions were performed at the 802.11b bit-rate of 11 Mbps. All of the subsequent experiments took place in a room measuring sixteen square meters within a residential neighborhood. Remote APs were detected on channels 1 (-92 dBm), 6 (-84 dBm), and 11 (-97 dBm) at the test site during testing.

In each experiment, a large 100 MB file was transmitted over the primary WiFi channel using UDP socket transfers. The background noise level was measured using one of the RT2570 interfaces operating in monitor mode and was verified using the Wi-Spy spectrum analyzer. The average noise level at the test site was reported by this device to be -99 dBm, with some occasional fluctuations at various channels, especially 1, 6, and 11, due to intermittent activity on remote networks. The monitor nodes also reported the power on each channel due to activity on remote WiFi networks. Most remote channels had powers in the range of -100 to -90 dBm, which we believe were beacon powers. These power measurements were not reported as noise by the device. However, spurious emissions with magnitudes of -80 or -70 dBm were observed on many channels, perhaps several times a minute. We believe that these spurious emissions were caused by remote user activity, though no exact measurements of remote beacons and noise were made due to the lack of access to state-of-the-art test equipment in our preliminary experiments.

Table II and Table III organize the RSSI and SINR data as reported by the Wi-Spy device during file transmission on each of the wireless channels, into a 2D matrix. The RSSI data in the tables were collected using Kismet's spectool_raw utility. A shell script was written to compute the average of the RSSI readings in each channel during file transfer activities. The SINR matrix was then computed from the RSSI matrix using: $SINR_{dBm} = Signal_{dBm} - (Noise + Interference)_{dBm}$. As confirmed earlier, the background noise level was reported by the monitor nodes to be -99 dBm most of the time. The interference power was reported per channel separately. The highlighted main diagonal in the matrices represents the active channels. Additional data on the RSSI and SINR are reported in the 2D and 3D MATLAB plots shown in Fig. 4 to Fig. 6.

In Fig. 5 and 6, each uniquely color-coded line represents a file transfer conducted at a particular WiFi channel. Given the file transfer on one channel, the signal strength was measured on each of the other channels using the Wi-Spy spectral analyzer.

Referring to the tables, the peak signal energy is always at the primary channel. Moving two channels away, i.e., a displacement of approx. 11 MHz, the signal attenuation is approx. 20 dB, yielding interference about 10 dBm above the IEEE spectral mask requirement. Moving 4 channels away causes an additional attenuation of (0 to 5) dB, yielding interference about 20 dBm above the IEEE spectral mask requirement. These results are likely due to interference from remote WiFi activity. The attenuation requirements specified by the IEEE 802.11b spectral mask shown in Fig. 2b apply to one device in isolation, and interference from other devices limits the SINRs in practice. Measurements of co-channel interference and SINRs for typical WiFi testbeds has not previously been quantified and published, so we cannot compare our results with any others.

Fig. 7a demonstrates per-channel activity in real-time along with a spectral density plot. These results were produced by the Chanalyzer Lite software under the Windows OS. Fig. 7b illustrates the power levels at different frequencies of the ISM spectrum during file transfers. The *test1* configuration uses a file transfer on wireless channel 1. The red specs represent the most frequently occurring energy readings. Therefore, during a file transmission on channel 1 the red outline indicates the mean RSSI levels to be around -70 dBm, with the RSSI dropping to about -100 dBm two channels away which conforms to the 802.11b spectral mask requirements.

Although the 802.11b bit-rate was configured as 11 Mbps, the average bit-rate was calculated from empirical measurements for verification. The average effective data rate was 3.96 Mbps, only 36.01% of the configured speed, which roughly coincides with the results of previously published data [6].

Referring to the 2D matrices and Fig. 4, 5, 6 and 7, the co-channel interference drops by about 20 dBm when the secondary channel is 2 channels away from the primary, as stated earlier. However, the interference increases when the secondary channel is 3 channels away. These observations are inconsistent with the IEEE spectral mask requirements. This pattern is repeated for every primary channel from 1-11, indicating that it cannot be explained by uncorrelated remote user activity. Referring to Fig. 2b, the spectral power density before the mast is applied is shown by the sinc() curves, and the interference power appears to increase at a distance of 3 channels. However, after the mask is applied the interference power should decrease at a distance of 3 channels. We compared our preliminary measurements with theoretical results on co-channel interference presented in [12], with similar observations. We plan to secure access to state-of-the-art measurement equipment and repeat the measurements, to precisely quantify the effects of remote WiFi activity.

V. CONCLUSION AND FUTURE WORK

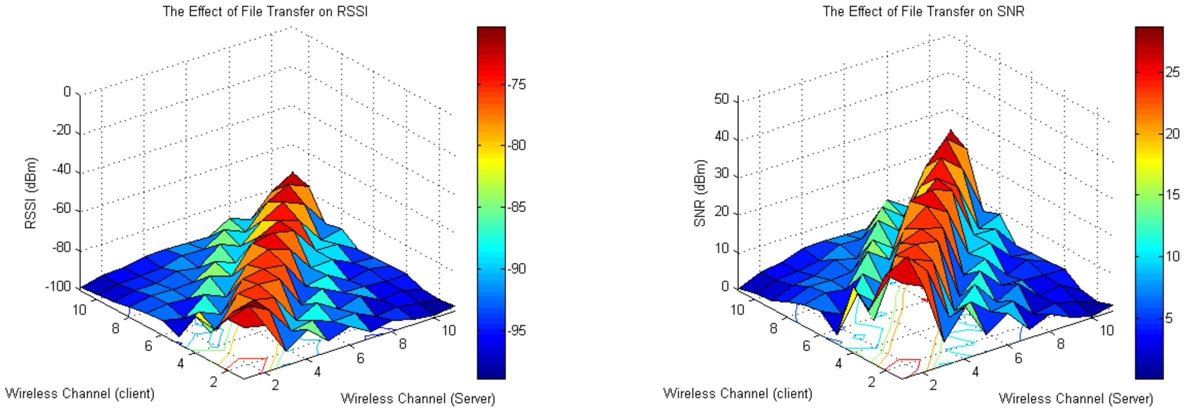
An 802.11b wireless mesh network testbed was developed using commercially available wireless transceivers and software. A single node design consists of multiple wireless transceivers which can be individually configured, i.e., the transmission / reception frequency, the transmission power, and data rate of each transceiver can be configured from a device driver in the Linux OS. Each node can be extended in several ways. Multiple wireless transceivers can be added to one node, to emulate a larger network virtually. Alternatively, multiple nodes can be deployed over a large geographic area, to implement a large mesh network as shown in Fig. 1. The optimization of a large network requires realistic statistics on co-channel interference and SINRs. Our testbed was configured to enable a large UDP file transfer on one channel over a short distance, and RSSI and SINR measurements were recorded on all other channels. Our measurements indicate that at a displacement of 2 channels or 10 MHz, the signal attenuation is -20 dBm. At a displacement of 4 channels or 20 MHz, the signal attenuation varies from -20 dBm to -25 dBm. This data indicates that interference from other WiFi networks and other microwave devices in the 2.4 GHz band is noticable in a

TABLE II
WI-SPY RSSI DATA (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	**-73.3302**	-75.9277	-92.6226	-85.1258	-94.3459	-90.2987	-96.5094	-94.1855	-96.9057	-98.4025	-97.3459
ch.2	-73.4455	**-70.2885**	-75.8846	-90.1314	-87.9647	-92.4359	-91.4103	-96.7564	-95.3974	-96.9263	-98.9359
ch.3	-85.1741	-77.8892	**-75.2816**	-77.3924	-92.6424	-87.4842	-94.0728	-90.75	-96.0696	-95.1709	-97.9272
ch.4	-81.2097	-92.0516	-76.6419	**-75.329**	-76.4194	-93.1742	-87.9548	-93.6548	-94.2032	-94.6935	-94.7806
ch.5	-96.5159	-87.3535	-91.8662	-77.5414	**-75.6401**	-76.9682	-91.5159	-88.9936	-95.1879	-92.9586	-95.2675
ch.6	-92.5466	-95.135	-86.2605	-90.8296	-77.9711	**-73.7235**	-77.0643	-89.8682	-89.1576	-94.4373	-95.4019
ch.7	-93.2748	-91.9457	-92.8978	-84.607	-88.4633	-74.754	**-73.4377**	-75.5272	-89.147	-89.5335	-95.5495
ch.8	-94.9108	-92.4936	-92.7803	-92.4936	-85.7038	-89.6338	-80.2834	**-74.6561**	-78.6688	-91.8631	-89.6752
ch.9	-96.9455	-94.6314	-94.0256	-91.5577	-93.0897	-84.7596	-89.2853	-79.3109	**-73.3205**	-78.2468	-91.4263
ch.10	-97.3462	-95.6282	-95.0897	-94.1538	-91.5032	-92.0192	-85.2853	-89.6859	-78.2756	**-72.4231**	-77.1859
ch.11	-98.4487	-95.859	-95.2179	-93.2276	-93.0577	-93.2692	-93.4551	-87.5897	-91.4038	-80.9583	**-74.5032**

TABLE III
WI-SPY SINR DATA (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	**25.6698**	23.0723	6.3774	13.8742	4.6541	8.7013	2.4906	4.8145	2.0943	0.5975	1.6541
ch.2	25.5545	**28.7115**	23.1154	8.8686	11.0353	6.5641	7.5897	2.2436	3.6026	2.0737	0.0641
ch.3	13.8259	21.1108	**23.7184**	21.6076	6.3576	11.5158	4.9272	8.25	2.9304	3.8291	1.0728
ch.4	17.7903	6.9484	22.3581	**23.671**	22.5806	5.8258	11.0452	5.3452	4.7968	4.3065	4.2194
ch.5	2.4841	11.6465	7.1338	21.4586	**23.3599**	22.0318	7.4841	10.0064	3.8121	6.0414	3.7325
ch.6	6.4534	3.865	12.7395	8.1704	21.0289	**25.2765**	21.9357	9.1318	9.8424	4.5627	3.5981
ch.7	5.7252	7.0543	6.1022	14.393	10.5367	24.246	**25.5623**	23.4728	9.853	9.4665	3.4505
ch.8	4.0892	6.5064	6.2197	6.5064	13.2962	9.3662	18.7166	**24.3439**	20.3312	7.1369	9.3248
ch.9	2.0545	4.3686	4.9744	7.4423	5.9103	14.2404	9.7147	19.6891	**25.6795**	20.7532	7.5737
ch.10	1.6538	3.3718	3.9103	4.8462	7.4968	6.9808	13.7147	9.3141	20.7244	**26.5769**	21.8141
ch.11	0.5513	3.141	3.7821	5.7724	5.9423	5.7308	5.5449	11.4103	7.5962	18.0417	**24.4968**



(a) RSSI MATLAB plot

(b) SNR MATLAB plot

Fig. 4. The effect of file transfers on the ISM band.

practical mesh deployment. Our measurements were made in the early hours of the morning, and it is expected that the SINR may drop during regular business hours when more activity on remote WiFi networks will be present. We plan to quantify the interference due to remote users more thoroughly once access to state-of-the-art measuring equipment is secured. The work can be extended in several ways. The current testbed uses 802.11b transceivers with omni-directional antenna. Currently, open-source Linux-based device drivers for 802.11n devices are available but they are unstable. The same experiments can likely be performed within a year or two using the latest generation 802.11n transceivers, open-source Linux-based device drivers, with MIMO directional antenna. We expect 802.11n devices to offer a significant increase in throughput with improvements to the co-channel interference and SINR measurements.

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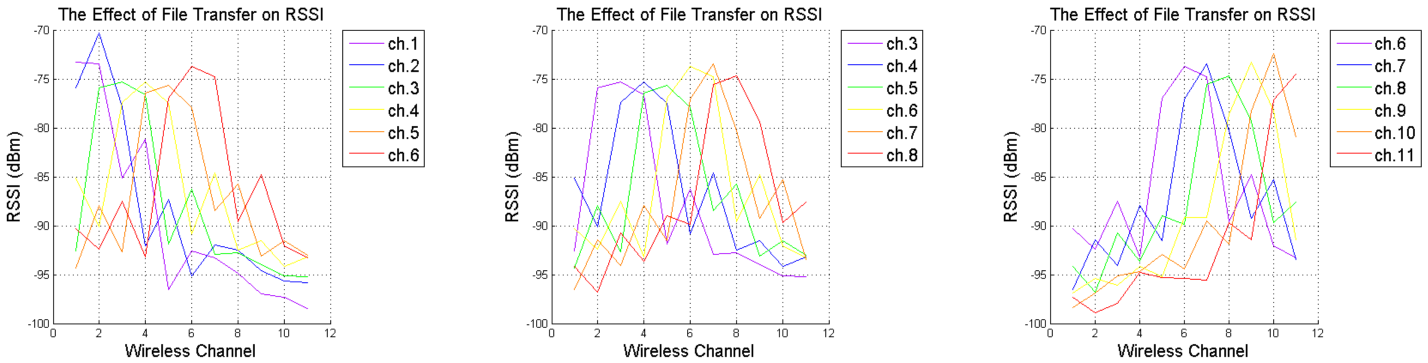
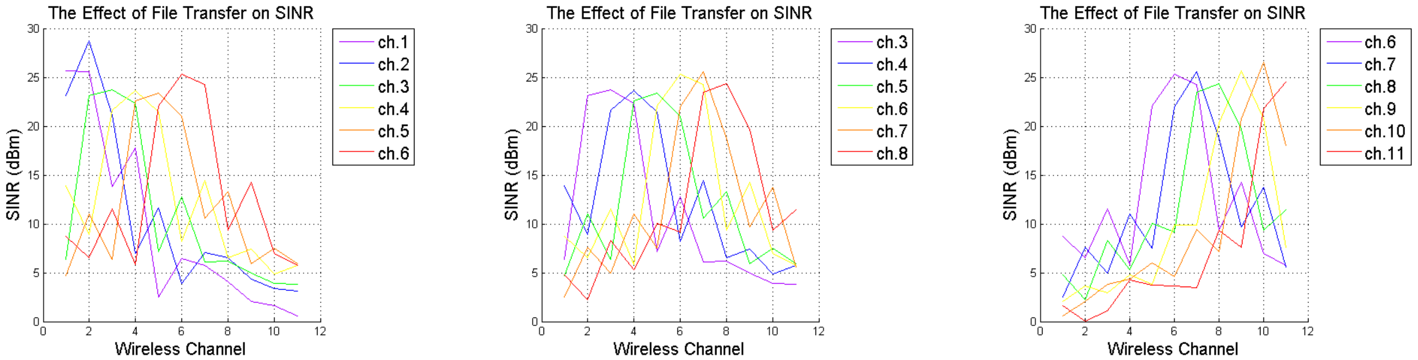


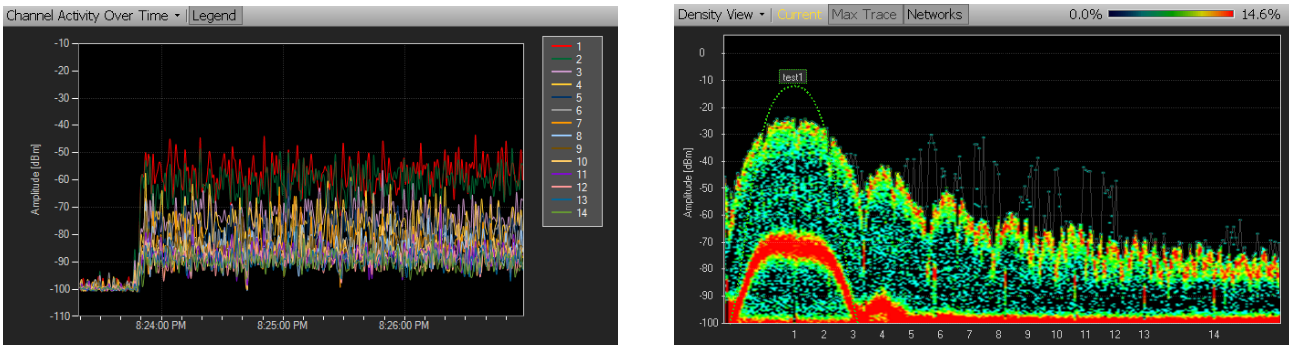
(a) File transfers on channels 1-6 (b) File transfers on channels 3-8 (c) File transfers on channels 6-11

Fig. 5. The effect of file transfer on RSSI.



(a) File transfers on channels 1-6 (b) File transfers on channels 3-8 (c) File transfers on channels 6-11

Fig. 6. The effect of file transfer on SINR.



(a) RSSI Before and During File Transmission (b) RSSI Distribution Due to File Transmission

Fig. 7. The effect of a channel 3 file transfer on the ISM band.

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