

# Experimental Study of 802.11n Network

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**Abstract**— Commercial solution for 802.11n has been made available in the market for quite some time. It is steadily gaining popularity due to its promise of maximum physical (PHY) data rate up to 600Mbps. However, the 802.11n firmware is not publicly available compared to the 802.11a/b/g firmware. Thus, we hardly found any experimental study on 802.11n from the wireless local area network (WLAN) research community using commercial 802.11n solution. We have had the opportunity to access the 802.11n firmware due to the development works carried out in our institute. In this paper, we have conducted the measurement study on the 802.11n network deployment issues raised by the WLAN research community. We believe that this paper is indeed useful for system administrators for 802.11n network planning and deployment.

**Keywords**— Wireless LAN, 802.11n, Deployment, Experimental Study, Lab Measurement

## I. INTRODUCTION

IEEE Standard Board has ratified the IEEE 802.11n amendment and the publication of the amendment is scheduled for mid-October 2009 [1]. However, Wi-Fi Alliance has begun its certification program for 802.11n draft 2.0 as early as June, 2007 [2] and this has prompted WLAN chipset makers, such as Atheros, Ralink, Intel, Marvel and etc. to come out with their 802.11n draft-2.0 market solutions. The 802.11n draft-2.0 solutions only require firmware upgrade to comply with the finalized 802.11n. This is due to the core features of 802.11n draft-2.0 will probably remain the same with finalized 802.11n. 802.11n builds on previous 802.11 standards by adding multiple-input multiple-output (MIMO), 40MHz channel bonding operation to the physical (PHY) layer, as well as frame aggregation and enhanced block acknowledgement (ACK) to the medium access control (MAC) layer [3]. Majority of the 802.11n draft-2.0 solutions available in the market support both 2.4GHz band and 5GHz band and are backward compatible with 802.11b/g in 2.4GHz band and 802.11a in 5GHz band.

There are several open source drivers for 802.11a/b/g chipset, such as acx100 [4], b43 [5], ipw2200 [6], rtl-wifi [7], madwifi [8] and etc. The research community has long benefits from the open source 802.11a/b/g driver. In

example, Doerr [9] has developed a cognitive MAC framework based on Atheros AR5212 chipset by modifying the Madwifi driver. Besides, the experimental study using Atheros/Madwifi chipset/driver pair has lead to interesting findings in [10]. But until today, the 802.11n open source driver is still in the early stage of development. To the best of our knowledge, the ath9k [11] and the iw4965 [12] are the only two available 802.11n drivers for research community. But both of them are still considered under development and no master mode is supported for the time being. Thus, the research community is still concentrate on simulation study and not yet able to conduct any meaningful experimental study related to 802.11n network. In such a case, it may particularly difficult for system administrator to plan or deploy their 802.11n network.

Due to the development works in our institute, we have gained the opportunity to study one of the popular 802.11n chipsets in the market, Atheros AR9160 incorporated with AR9106 chipsets and also the Atheros Linux 802.11n driver. Before porting it to different hardware architectures, we have modified the driver to permit us to configure certain parameters during compilation and run-time. With these, we have managed to conduct the measurement related to the enhanced features found in 802.11n. At the same time, we have successfully setup a testbed consists of IEEE 802.11n station also referred as High Throughput (HT) station (STA) and non-HT STA to study the 802.11 network deployment issues: coexistence with the legacy 802.11a/b/g devices and interoperability of these devices in the 802.11n network. We believe that our measurement study can be a good reference for system administrator to reap the benefits on 802.11n using one of the most popular chipsets in the market.

In section II, we briefly explain the 802.11n enhance features. The 802.11n deployment issues are discussed in section III. In section IV, the hardware/software platform used for measurement is described. The methodology for our measurement is presented in section V. We summarized our findings and results in section VI and conclusion can be found in section VII.

## II. 802.11N ENHANCED FEATURES

As mentioned in [3], the core features found in draft-2.0 are

considered stable and this is further confirmed by Wi-Fi Alliance's press statement [13]. The mandatory and optional features for PHY later can be summarized as follow:

- a. Spatial multiplexing: 1 or 2 spatial streams as mandatory and 3 or 4 spatial streams as optional.
- b. Channel bandwidth: 20MHz with highest encoder rate 5/6 as mandatory and 40MHz and the use of 400ns Short Guard Interval (SGI) as optional.
- c. Interoperability with legacy 802.11a/b/g device: Mixed format as mandatory and Greenfield format as optional.
- d. MIMO enhancement: basic spatial-division multiplexing (SDM) as mandatory and transmit beamforming (TxBF) and space-time block coding (STBC) as optional.
- e. Error correction: convolution code as mandatory and low density parity check (LDPC) code as optional.

Further explanation on these features can be found at [3].

Development of 802.11n is mainly to provide the capability of at least 100Mbps throughput for MAC layer. Thus, the MAC efficiency has to be improved to achieve that. The MAC enhancement features are listed as follow:

- a. Frame aggregation as mandatory: MAC protocol data unit aggregation (A-MPDU) and MAC service data unit aggregation (A-MSDU).
- b. Block ACK as mandatory.
- c. Protection mechanism for coexistence between 40MHz bandwidth HT device and 20MHz bandwidth HT device and legacy 802.11a/b/g device as mandatory.
- d. Optional features, such as Reduced Interframe Spacing (RIFS) burst in Greenfield deployment, reverse direction protocol, fast link adaptation and TxBF control.

Basically, A-MSDU concatenates multiple MSDUs destined to the same receiver as one single MPDU. Its maximum length can be either 3839 bytes or 7935 bytes [14]. An access point (AP) usually receives frame from its Ethernet interface, translates it into a single 802.11n frame and send to a client. In this case, the A-MSDU aggregation is applied for the data destined to the same client. But for client connected to an AP, since all the traffic has to go through the same AP, the client can aggregate MSDUs destined to different Ethernet addresses. A-MSDU resides at the top of the MAC and can be implemented in software.

On the other hand, A-MPDU joins multiple MPDU subframes with a single PHY header. The maximum length for an A-MPDU is 65,535 bytes, which is equivalent to maximum length of the physical service data unit (PSDU). The utmost number of subframes is 64 with the size of each subframe limited to 4095 bytes. As specified in the standard, all the MPDUs must be addressed to the same receiver address. So, an AP or clients need to translate the Ethernet frame according the 802.11 format and collect 802.11 frames for a common destination. A-MPDU is considered located at

the bottom of MAC and requires the partial hardware implementation. A-MPDU is made possible using the Block ACK feature. This ensures that multiple MPDUs are only acknowledged by a single block ACK. In previous standard, every single MPDU transmitted by the sender is required to be acknowledged by the recipient. For these two mechanisms, A-MPDU requires more overhead compared to A-MSDU since the 802.11 frame header is larger than the Ethernet header. Besides, A-MPDU requires encryption on all the MPDU subframes while A-MSDU only requires the encryption on the aggregated frame.

To ensure backward compatibility with 802.11b/g device operating in 2.4GHz band and 802.11a device operating in 5GHz band, HT-Mixed mode preamble must be supported by the HT device. Optionally, the HT devices can use HT-Greenfield if it operates in a *pure* 802.11n network. To further protect its transmission from legacy 802.11a/b/g device, Request-to-Send/Clear-to-Send (RTS/CTS) or CTS-to-self [15][16] is used by the HT device. Protection mechanism adds additional overhead in radio preamble and 802.11 management frames and subsequently reduces the effective throughput of HT devices.

### III. 802.11N DEPLOYMENT ISSUES

The use of 40MHz channels in WLANs significantly increases the data rate in the network as shown in Table I. The physical data rate up to 300Mbps can only be achieved using at least two data streams and 40MHz channel bandwidth. The 2.4GHz band is not more than 100MHz wide and provides only one non-overlapping 40MHz channels. Based on our country's regulator policy, the 5GHz band is ranging from 5150MHz to 5350MHz [17] and this offers 4 non-overlapping 40MHz channels. Besides, the 5GHz system faces less interference compared to those operated in the 2.4GHz band. Therefore, the 5GHz band is suitable for the 802.11n deployment. However, we still need to consider the following scenarios:

- a. The HT AP operates in 40MHz channel with the presence of overlapping legacy AP which is operating on the primary or the secondary channel of the HT AP.
- b. The HT AP operates in 40MHz channel but not all the associated STAs use the 40MHz channel.
- c. The HT AP is associated with legacy STAs.

Even though 802.11n deployment can be moved to 5GHz band to mitigate the radio frequency (RF) interference, we still have to deal with legacy AP and STA. Whenever there is legacy devices, the protection mechanism is triggered in the AP. Simulation study in [19] has shown that protection overhead could degrade the effective throughput of 802.11n network. The simulation results in [20] shows that the overall throughput of 40MHz Basic Service Set (BSS) and legacy BSSs are increased if Clear Channel Assessment (CCA) is used in the overlapping channel. We intend to find out more on how our AP behaves in the mentioned scenarios.

**Table 1. Maximum Achievable Data Rate for 802.11 a/b/g/n in Mbps**

| Operating Mode               | 20MHz Channel |              | 40MHz Channel |            |
|------------------------------|---------------|--------------|---------------|------------|
|                              | 1 Stream      | 2 Stream     | 1 Stream      | 2 Stream   |
| 802.11b                      | 11            |              |               |            |
| 802.11a/g                    | 54            |              |               |            |
| 802.11n 2.4GHz with GI 800ns | 65            | 130          |               |            |
| 802.11n 2.4GHz with GI 400ns | <i>72.2</i>   | <i>144.4</i> |               |            |
| 802.11n 5GHz with GI 800ns   | 65            | 130          | <i>135</i>    | <i>270</i> |
| 802.11n 5GHz with GI 400ns   | <i>72.2</i>   | <i>144.4</i> | <i>150</i>    | <i>300</i> |

\* The optional data rates are represent with bold and italic figures.  
 \* The 40MHz channel operation is not certified by Wi-Fi Alliance [18].

**IV. HARDWARE/SOFTWARE PLATFORM FOR MEASUREMENT**

We have ported the Atheros Linux driver to two different hardware platforms: our own customized TM-AR7100 featuring Atheros AR7161 Wireless Network Processing Unit (WNPU) and ADI Engineering Pronghorn Single Board Computer (SBC) featuring Intel IXP425 Network Processor. The hardware features of these two platforms are listed in Table II. Instruction cache in TM-AR7100 is slightly higher to reduce the number of instruction fetching happened between the external RAM and the processor. Both of our hardware platforms are running Linux operating system. This provides us the flexibility to configure the platform as a bridge [21] or a router. A bridge connects two Ethernet segments, one for wired interface and another one for wireless interface, using a single IP subnet. Packet forwarding is carried out based on Ethernet address rather than IP address. As a router, IP address is indeed used for forwarding purpose. A wireless bridge requires 4 MAC addresses to be used in the 802.11 frame format so that the frame can be safely arrived at the targeted destination.

**Table 2. Hardware Platform Comparison**

| Features                              | TM-AR7100                                 | Pronghorn SBC-250                         |
|---------------------------------------|---|---|
| Processor Architecture                | AR7161 WNPU - MIPS32® 24K® Processor Core | Intel® IXP425 Network Processor           |
| Processor Speed                       | 680MHz                                    | 533MHz                                    |
| Ethernet Interface                    | Gigabit                                   | Fast Ethernet                             |
| RAM Availability                      | 64M bytes                                 | 64M bytes                                 |
| Cache Size                            | Instruction: 64K bytes<br>Data: 32K bytes | Instruction: 32K bytes<br>Data: 32K bytes |
| Concurrent Support for 802.11n module | 4   | 2   |

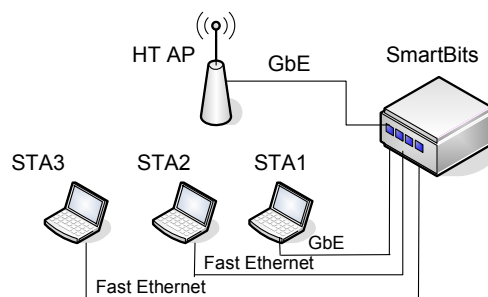
The mini-PCI radio card slotted into our hardware platforms consists of Atheros AR9160 MAC/Baseband processor and AR9106 3x3 MIMO Radio. The AR9160 integrates the MAC, baseband processor and analog-to-digital and digital-to-analog converters (ADC/DAC) into an all-CMOS device. Meanwhile, the AR9106 provides up to

three integrated transmit chains and receive chains (3Tx/3Rx). Thus, this Atheros XSPAN solution is able to support two spatial data streams with 3Tx/3Rx. Since the throughput is determined by the number of data streams, increasing the radio chains to three is mainly to improve reliability and robustness in data transmission and has nothing to do with throughput enhancement. So, the theoretical physical data rate up to 130Mbps for 20MHz channel and 300Mbps for 40MHz channel can be achieved. The mandatory features listed in the 802.11n draft-2.0 standard are complied in this chipset, including the optional features, such as SGI. One of the features that worth mentioned here is CCA to ensure coexistence with 802.11a/b/g devices while using 40MHz channel operation [22]. The MAC layer functionalities for AR9160 are actually partitioned into hardware/software combination. Time critical functions, such as ACK generation, channel access using Enhanced Distributed Coordination Function (EDCF) and etc., are implemented in hardware. However, software from the host is still required to control the processing of transmit and receive queue. This is actually part of tasks handled by the Atheros Linux driver. By using the Atheros Linux driver, we are able to configure the chipset to operate in different operating modes: 802.11a, 802.11b, 802.11g or 802.11n.

**V. MEASUREMENT METHODOLOGY**

A testbed based on network topology shown in Figure 1 is setup to conduct our experiments. This setup contains the following components:

- HT AP based on the TM-AR7100 hardware platform
- STA1 based on the TM-AR7100 hardware platform
- STA2 based on the TM-AR7100 hardware platform
- STA3 based on the Pronghorn SBC-250 hardware platform
- Spirent SmartBits network performance system
- AirPcap 802.11a/b/g/n and Wireshark network protocol analyzer [23]



**Figure 1. Network Topology for 802.11n Experiments**

A dedicated hardware, the Spirent SmartBits 600B which consists of two 10/100/1000Base-T or GbE Ethernet ports and

six 10/100Base-T or Fast Ethernet ports, is used for generating and capturing the data. Using the dedicated hardware for traffic analysis helps us to eliminate the performance bottleneck that occurs in most of the software based performance analysis tools. In our setup, the HT AP and the STA1 are connected to two separate GbE ports available in the SmartBits. In the mean time, the STA2 and the STA3 are connected to two separate Fast Ethernet ports of the SmartBits. During the experiments, the 802.11a/b/g/n network protocol analyzer, known as Wireshark [23], is brought up to monitor the wireless traffic. This setup is used to conduct the following experiments:

- a. Achievable downstream throughputs for 1, 2 and 3 HT STAs with or without frame aggregation
- b. Achievable upstream throughput for HT STA using A-MSDU
- c. Achievable downstream throughput for HT STA coexisting with legacy STA
- d. Achievable downstream throughput for HT STA coexisting with legacy AP

For measurement in case (b), our testbed is modified as depicted in Figure 2. An additional switch is added to accommodate the data collection in the SmartBits.

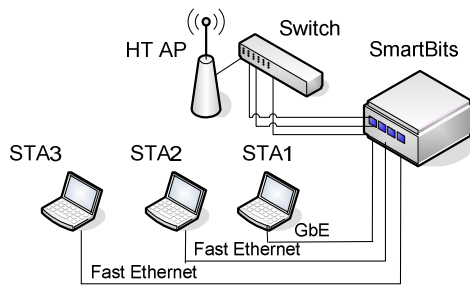


Figure 2. Network Topology for 802.11n Experiments with additional Fast Ethernet Switch

All our experiments are carried out in the shielded room. Besides, the 5GHz band is chosen for our experiments to further mitigate the heavy interferences in the 2.4GHz band. We have modified the Atheros Linux driver to allow us to configure certain parameters during runtime. The following parameters are configurable in our firmware resided in the HT AP and the STAs:

- Select the operating mode: 802.11a, b, g and n
- Select the 20/40MHz channel operation
- Enable or disable A-MPDU
- Enable or disable A-MSDU
- Set the number of subframes in A-MPDU
- Set the size of A-MPDU
- Set the size of A-MSDU

Throughout the experiments, the HT AP is configured to operate in the 40MHz channel bandwidth. The Tx/Rx radio chains for the HT AP and HT STA are set to 2/2 instead of 3/3. However, this does not affect the effective throughput as

discussed in previous section. SGI is enabled by default. A-MPDU is enabled by default with total size of 65,535 bytes and 64 subframes. However, A-MSDU is disabled by default. All the above settings are used for our measurements unless we cite otherwise. Receive Signal Strength Indication (RSSI) around 70 is recorded or approximately -25dBm of signal level for all the STAs connected to the HT AP. Frame sizes of 64, 128, 156, 512, 1024, 1280 and 1518 bytes are defined in the SmartBits. To differentiate the 802.11n STAs in our further discussion, the 802.11n STA operating in 40MHz channel bandwidth is named as HT40 STA and the STA operating in 20MHz channel bandwidth is known as HT20 STA.

## VI. RESULTS

### A. Router or Bridge

Figure 3 illustrates the UDP downstream throughput results for 1 HT40 STA in Mbps. The HT AP is configured as a bridge or a router to compare the performance between these two different modes in our hardware platform. The initial traffic load is 25Mbps, and it is increased up to 300Mbps with the increase of frame size (i.e., 64/128/256/512/1024/1280/1518 bytes). The similar traffic load is applied to other measurements as well. Using the "top" utility, we found out that our machine is still not yet under heavy interrupt load with 300Mbps traffic injection. The results shown in Figure 3 indicate that there is no significant difference between these two modes. An AP operating as a bridge must enable its Wireless Distribution System (WDS) mode. Thus, 4 MAC addresses are required in the 802.11 frame header for each 802.11 frame. Meanwhile, an AP operating as a router requires more processing time for stripping and appending the IP address and also the MAC address but it uses only 3 MAC addresses in the 802.11 frame header. We have further verified these using the network analyzer.

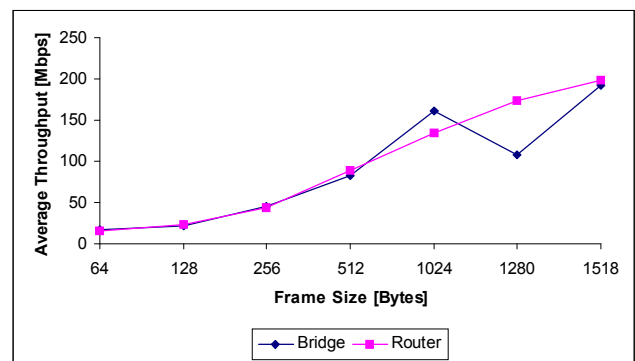


Figure 3. Throughput vs. Increased Traffic Load for Bridge and Router

### B. Frame Aggregation in HT STA

Figure 4 illustrates the UDP downstream throughput results for 1 HT40 STA in Mbps with or without frame aggregation. The maximum achievable downstream throughput with frame

aggregation for 1518 bytes frame size is approximately 200Mbps compared to 41.76Mbps without frame aggregation. However, there is no significant advantage for frame size as small as 64 bytes. It is worth mentioned that the network analyzer indicates that our AP can only achieve the maximum frame size of 1538 bytes in an A-MPDU subframe. This is actually the typical network scenario because the incoming Ethernet frame size for an AP is physically limited to 1518 bytes.

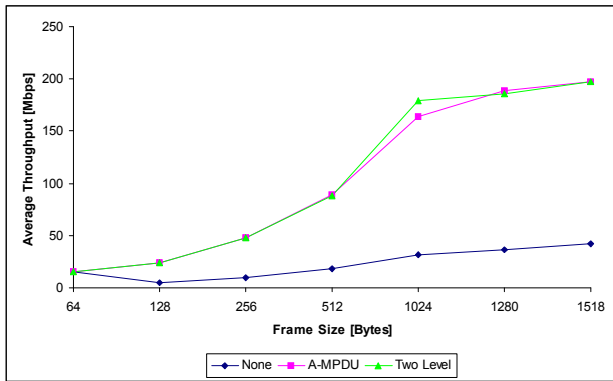


Figure 4. Throughput vs. Increased Traffic Load for Frame Aggregation

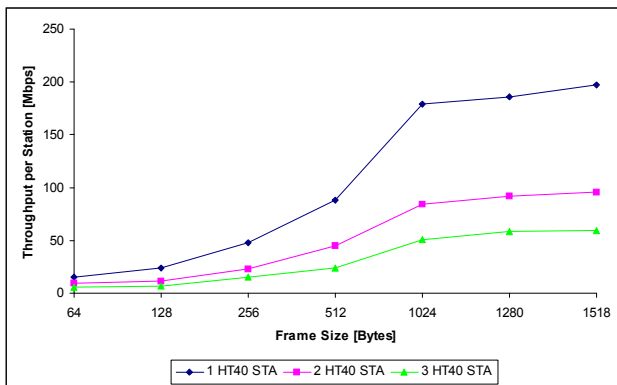


Figure 5. Throughput vs. Increased Traffic Load for 1, 2 and 3 HT STA

Two-level frame aggregation means that enabling both the A-MPDU and the A-MSDU in the HT AP. By using the network analyzer, we have found out that two-level frame aggregation is only applicable to 64 bytes frame size. Up to 32 A-MSDU subframes with 72 bytes in each subframe can be observed in our analysis. However, even in 64 bytes frame size, there is no significant throughput enhancement found in two-level frame aggregation compared to A-MPDU frame aggregation. Figure 5 illustrates the UDP downstream throughput results for 1, 2 and 3 HT40 STA in Mbps. The achievable throughput per station for 1518 bytes frame size is approximately 200Mbps for 1 HT40 STA, 98Mbps for 2 HT40 STA, 60Mbps for 3 HT40 STA. Generally, the results in Figure 5 show that the throughput is equally distributed

between the stations associated to the HT AP.

### C. A-MSDU for Upstream Throughput

The TCP traffic load of 20Mbps is generated from 1 HT40 STA to the HT AP. The frame size is defined as 76 bytes which is the minimum size permitted in the SmartBits for TCP frame. This small frame size is selected for measurement since the A-MSDU is not applicable to large frame size. The aggregated upstream throughput results in Mbps are shown in Figure 6. The increment of 0.4 percent in the throughput is achieved if the A-MSDU is enabled in the HT STA. If small TCP frames, such as TCP ACK, are aggregated during the packet transmission, the latency for acknowledging the TCP packets can be reduced. Unnecessary TCP retransmission due to retransmission timeout can be subsequently avoided. In overall, the effective throughput of the network can be increased.

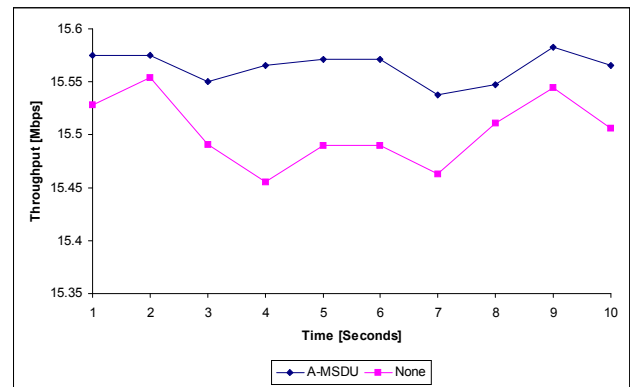


Figure 6. Throughput in 10 seconds Measurement

### D. Impact of Legacy STA in 802.11n Network

Figure 7 illustrates the UDP downstream throughput results for 2 STA in Mbps. The maximum throughput per station can only be achieved in the scenario of 2 HT40 STA. If either 1 HT20 STA or 1 legacy 802.11a STA associates with the HT AP, the throughput for the HT40 STA is also degraded. The throughput of the HT40 STA for 1518 bytes frame size can be reduced to 40.16Mbps, a 60 percent decrement, if a HT20 STA joins the network, known as HT 20MHz protection mode. If the HT AP has to serve a legacy STA or in the HT mixed mode operation, the throughput of the HT40 STA for 1518 bytes frame size can be reduced to 22.13Mbps. A 78 percent decrement compares to the scenario of 2 HT40 STA.

### E. Impact of Overlapping BSS on 802.11n Network

The UDP downstream throughput results for 1 HT40 STA in Mbps coexisting with a legacy AP are illustrates in Figure 8. A legacy 802.11a AP is activated and located less than 1 meter from the HT AP. The 802.11 beacon frame generated by the legacy AP is in 100ms interval. This has caused the HT AP to switch to HT non-member protection mode. We have verified this by observing the HT Information Element (IE) in the beacon frame generated by the HT AP. The average throughput

for HT STA coexisting with legacy AP is not significantly degraded if there is no activity in the legacy AP except the beacon generation. However, the throughput of the HT40 STA is 37Mbps less, a 19 percent decrement, for 1518 bytes frame size if there is packet transmission happening in the overlapping BSS.

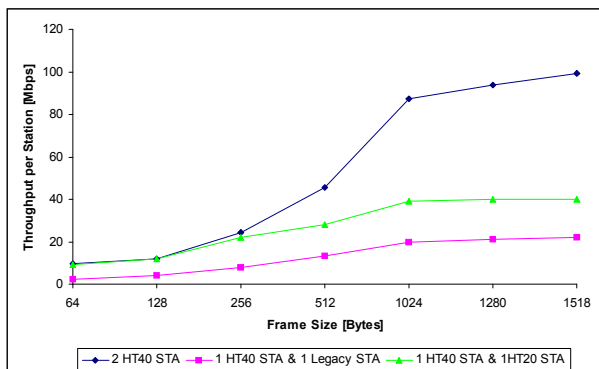


Figure 7. Throughput vs. Increased Traffic Load for HT STA coexisting with Legacy STA

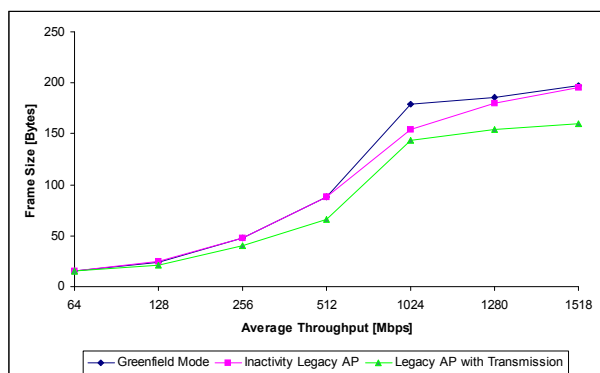


Figure 8. Throughput vs. Increased Traffic Load for HT STA coexisting with Legacy AP

## VII. CONCLUSIONS

In this paper, we have conducted a comprehensive experimental study of 802.11n network using commercial 802.11n chipset. Our measurement results show that the overall throughput is not affected whether the AP acts as a router or a bridge. Besides, we can conclude that the downstream throughput for HT STA operating in 40MHz channel could be severely degraded if a legacy STA or a HT STA operating in 20MHz channel joins the 40MHz BSS. Thus, the maximum throughput of 802.11n is achievable only if all the HT STAs operates using the same channel bandwidth as the HT AP. In our measurement, we also found out that the HT AP performs fairly well in coexistence of overlapping BSS. This may partly due to CCA implemented in the Atheros chipset.

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