The Impact of Channel Bonding on 802.11n Network Management

5 Ghz Band Experimentation Environment

Disabling CCA

We disable CCA (actually disable bss neighbor /force 40 MHz channels in hostapd) by changing the src/ap/hw_features.c file from the source code of hostapd to ignore the overlapping BSSes. We actually modify the case where 20/40 MHz operation is not permitted by comment out iface->conf->secondary_channel = 0; DILLIGAF . Then we compiled our new hostapd and run it as executable in the compiled directory: (./hostapd -dd hostapd.conf)

Enabling 5Ghz Band

The problem is evident when executing hostapd with the -dd flag , in which case it lists the allowed channels. And none of the 5 GHz channels is listed. The underlying reason is the “no IR” part given in “iw list”, meaning no Initial Radiation, hence no access point allowed. The card was set to a "world" regulatory domain in EEPROM, therefore all channels in the 5GHz band have "No-IR" flag set.

So we solve it by edit drivers/net/wireless/ath/regd.c and neutralize the following functions with a “return” immediately after variable declarations. Or replace them with functions just returning immediately: ath_reg_apply_beaconing_flags() ath_reg_apply_ir_flags() ath_reg_apply_radar_flags()

Then we set the flag ATH_USER_REGD to 1.Then we had to recompile ath9k to get it to not restrict by EEPROM code. After the recompile we force the regulatory domain by running: sudo modprobe cfg80211 ieee80211_regdom=GR

Measurement Environment

- We generate constant bit-rate UDP traffic between the transmitter and receiver pairs using the iperf tool, with fixed packet sizes of 500 bytes. We monitor UDP flows and evaluate their performance in terms of MAC layer throughput.
- We disable the ath9k automatic rate selection scheme and control the transmission MCS using a set of custom scripts:

  ```
  while true; do cat /sys/kernel/debug/ieee80211/phy0/netdev:wlan0/stations/*/rc_stats; sleep 1; done;

  echo 0 > /sys/kernel/debug/ieee80211/phy0/rc/fixed_rate_idx
  ```

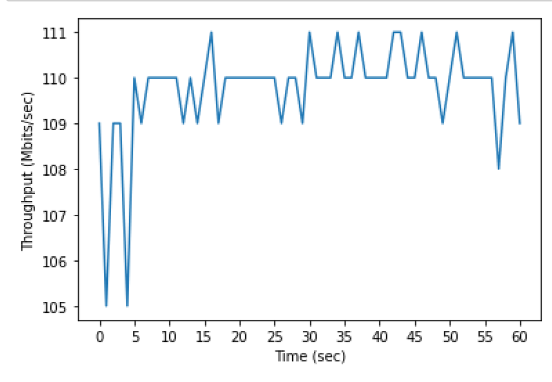
- We also control the channel width to determine the performance differences between operating on a 20MHz channel and switching to a wider 40MHz channel. We run our experiments for all supported MCS values. As a result, we identify the best MCS for each tested link and channel width configuration.
- We calculate the Duty Cycle of each case by taking the advantage of spectral measurements available at the PHY-layer of commercial 802.11 equipment.
- We identify two interference patterns from neighboring links : co-channel and adjacent channel interference.

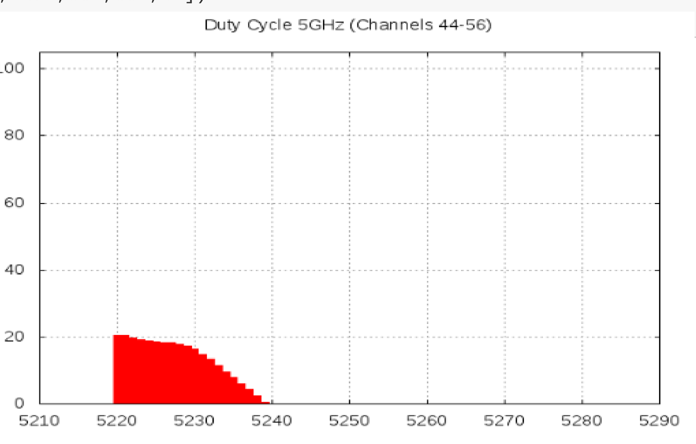
20 Mhz Under Test

20 Mhz Link

Best MCS: MCS23 , index: 27 (LGI 3)

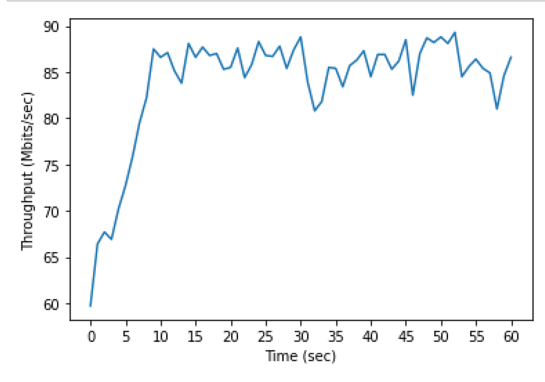
In [1]:
```python
from matplotlib import pyplot as plt
x = [ 0.0 , 1.0 , 2.0 , 3.0 , 4.0 , 5.0 , 6.0 , 7.0 , 8.0 , 9.0 ,10.0 ,11.0 ,12.0 ,13.0 ,14.0 ,15.0 ,16.0 ,17.0 ,18.0 ,19.0 ,20.0 ,21.0 ,22.0 ,23.0 ,24.0 ,25.0 ,26.0 ,27.0 ,28.0 ,29.0 ,30.0 ,31.0 ,32.0 ,33.0 ,34.0 ,35.0 ,36.0 ,37.0 ,38.0 ,39.0 ,40.0 ,41.0 ,42.0 ,43.0 ,44.0 ,45.0 ,46.0 ,47.0 ,48.0 ,49.0 ,50.0 ,51.0 ,52.0 ,53.0 ,54.0 ,55.0 ,56.0 ,57.0 ,58.0 ,59.0 ,60.0]
link_20 = [109 ,105 ,109 ,109 ,105 ,110 ,109 ,110 ,110 ,110 ,110 ,110 ,109 ,110 ,109 ,110 ,111 ,109 ,110 ,110 ,110 ,110 ,110 ,110 ,110 ,110 ,109 ,110 ,110 ,109 ,111 ,110 ,110 ,110 ,111 ,110 ,110 ,111 ,110 ,110 ,110 ,110 ,111 ,111 ,110 ,110 ,111 ,110 ,110 ,109 ,110 ,111 ,110 ,110 ,110 ,110 ,110 ,108 ,110 ,111 ,109]
plt.plot(x,link_20)
plt.xlabel("Time (sec)")
plt.ylabel("Throughput (Mbits/sec)")
plt.xticks([0 , 5 , 10 , 15 , 20 , 25 , 30 ,35 , 40 , 45 ,50 ,55 ,60])
plt.show()
```

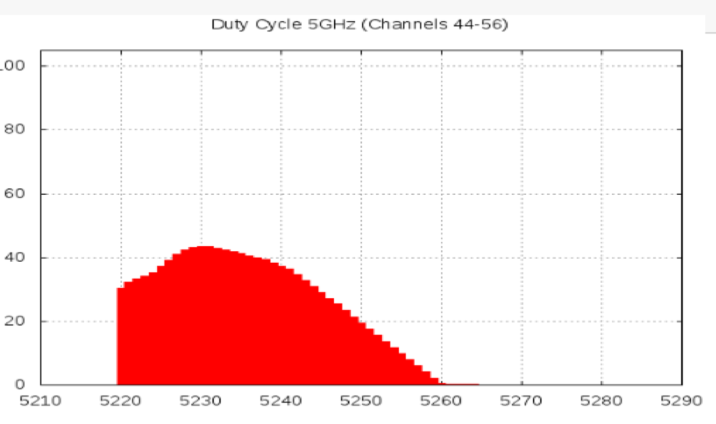




20 Mhz with 20 Mhz adjacent

In [2]:
```python
adj_20_20 = [59.7 ,66.4 ,67.7 ,66.9 ,70.2 ,72.7 ,75.8 ,79.5 ,82.2 ,87.5 ,86.6 ,87.1 ,85.1 ,83.8 ,88.1 ,86.6 ,87.7 ,86.8 ,87.0 ,85.3 ,85.5 ,87.6 ,84.4 ,85.8 ,88.3 ,86.8 ,86.7 ,87.8 ,85.4 ,87.4 ,88.8 ,83.9 ,80.8 ,81.8 ,85.5 ,85.4 ,83.4 ,85.7 ,86.3 ,87.3 ,84.5 ,86.9 ,86.9 ,85.3 ,86.2 ,88.5 ,82.5 ,87.0 ,88.7 ,88.2 ,88.8 ,88.1 ,89.3 ,84.5 ,85.6 ,86.4 ,85.4 ,84.9 ,81.0 ,84.6 ,86.6]
plt.plot(x,adj_20_20)
plt.xlabel("Time (sec)")
plt.ylabel("Throughput (Mbits/sec)")
plt.xticks([0 , 5 , 10 , 15 , 20 , 25 , 30 ,35 , 40 , 45 ,50 ,55 ,60])
plt.show()
```

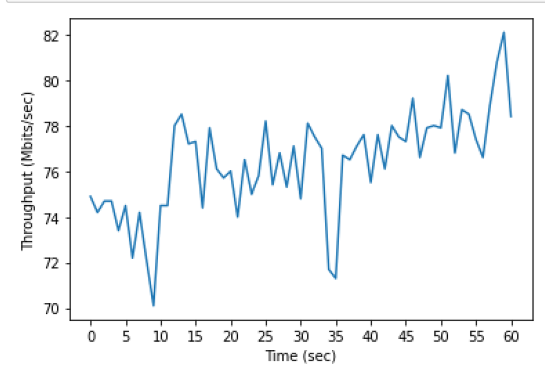


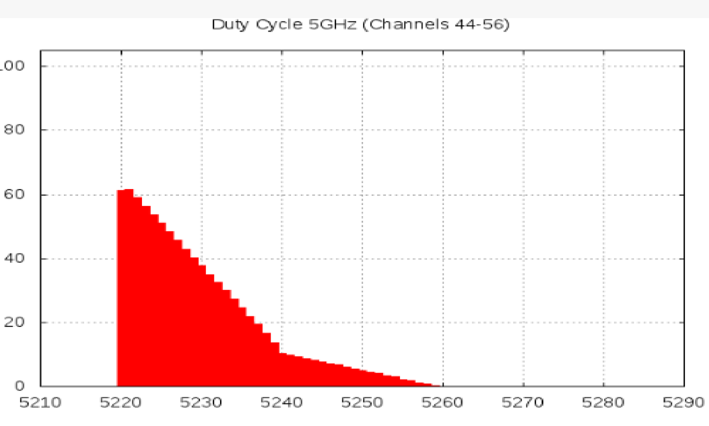


Nodes that operate on non-overlapping, yet adjacent, channels, as we see from the plot graph above, still suffer interference from channel leakage when power from transmissions on adjacent channels spills to neighboring channels.

20 Mhz with 40 Mhz adjacent

In [3]:
```python
adj_20_40 = [74.9 ,74.2 ,74.7 ,74.7 ,73.4 ,74.5 ,72.2 ,74.2 ,72.1 ,70.1 ,74.5 ,74.5 ,78.0 ,78.5 ,77.2 ,77.3 ,74.4 ,77.9 ,76.1 ,75.7 ,76.0 ,74.0 ,76.5 ,75.0 ,75.8 ,78.2 ,75.4 ,76.8 ,75.3 ,77.1 ,74.8 ,78.1 ,77.5 ,77.0 ,71.7 ,71.3 ,76.7 ,76.5 ,77.1 ,77.6 ,75.5 ,77.6 ,76.1 ,78.0 ,77.5 ,77.3 ,79.2 ,76.6 ,77.9 ,78.0 ,77.9 ,80.2 ,76.8 ,78.7 ,78.5 ,77.4 ,76.6 ,78.9 ,80.8 ,82.1 ,78.4]
plt.plot(x,adj_20_40)
plt.xlabel("Time (sec)")
plt.ylabel("Throughput (Mbits/sec)")
plt.xticks([0 , 5 , 10 , 15 , 20 , 25 , 30 ,35 , 40 , 45 ,50 ,55 ,60])
plt.show()
```

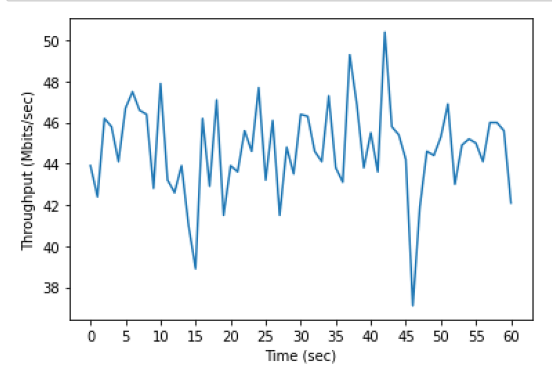


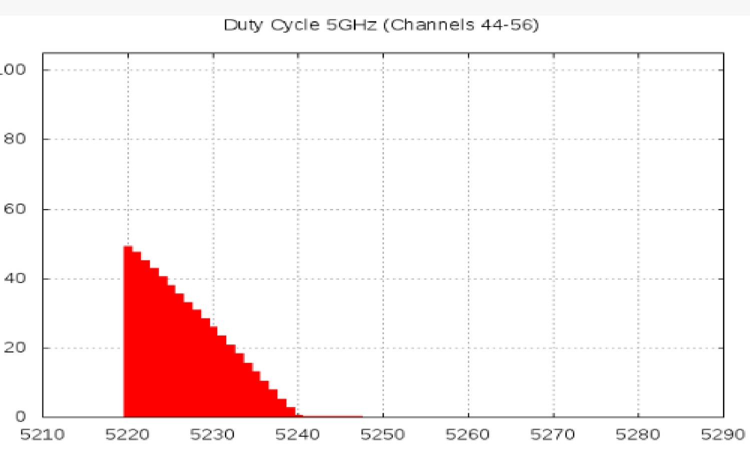


A 20MHz transmission has more energy than a 40MHz transmission and, thus, a 20MHz transmission is more easily detected. Therefore, for sufficiently strong interferers that activate carrier sensing, 20MHz adj performs better than 40MHz adj. That can be observed easily by comparing the two plot graphs above.

Two 20 Mhz sharing the same channel

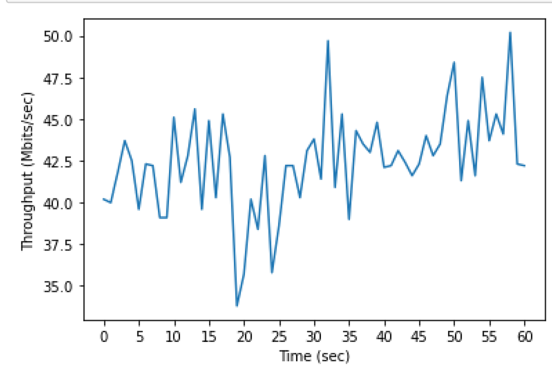
In [4]:
```python
same_20 = [43.9 ,42.4 ,46.2 ,45.8 ,44.1 ,46.7 ,47.5 ,46.6 ,46.4 ,42.8 ,47.9 ,43.2 ,42.6 ,43.9 ,41.0 ,38.9 ,46.2 ,42.9 ,47.1 ,41.5 ,43.9 ,43.6 ,45.6 ,44.6 ,47.7 ,43.2 ,46.1 ,41.5 ,44.8 ,43.5 ,46.4 ,46.3 ,44.6 ,44.1 ,47.3 ,43.8 ,43.1 ,49.3 ,46.9 ,43.8 ,45.5 ,43.6 ,50.4 ,45.8 ,45.4 ,44.2 ,37.1 ,41.9 ,44.6 ,44.4 ,45.3 ,46.9 ,43.0 ,44.9 ,45.2 ,45.0 ,44.1 ,46.0 ,46.0 ,45.6 ,42.1]
plt.plot(x,same_20)
plt.xlabel("Time (sec)")
plt.ylabel("Throughput (Mbits/sec)")
plt.xticks([0 , 5 , 10 , 15 , 20 , 25 , 30 ,35 , 40 , 45 ,50 ,55 ,60])
plt.show()
```

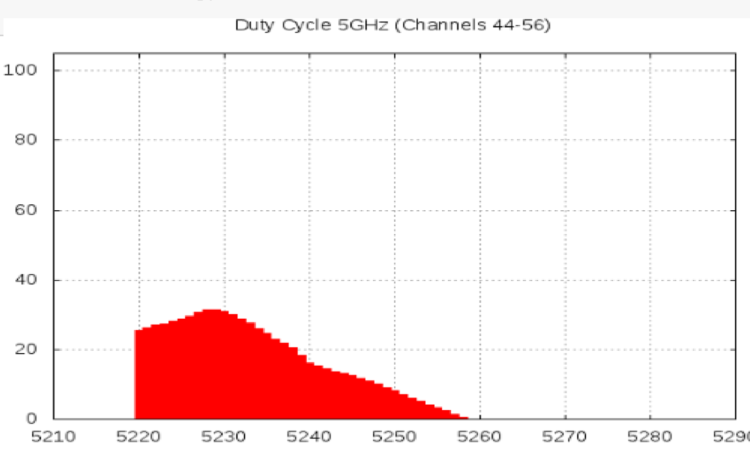




20 Mhz and 40 Mhz sharing the same channel

In [5]:
```python
same_20_40 = [40.2 ,40.0 ,41.8 ,43.7 ,42.5 ,39.6 ,42.3 ,42.2 ,39.1 ,39.1 ,45.1 ,41.2 ,42.8 ,45.6 ,39.6 ,44.9 ,40.3 ,45.3 ,42.7 ,33.8 ,35.7 ,40.2 ,38.4 ,42.8 ,35.8 ,38.6 ,42.2 ,42.2 ,40.3 ,43.1 ,43.8 ,41.4 ,49.7 ,40.9 ,45.3 ,39.0 ,44.3 ,43.5 ,43.0 ,44.8 ,42.1 ,42.2 ,43.1 ,42.4 ,41.6 ,42.3 ,44.0 ,42.8 ,43.5 ,46.4 ,48.4 ,41.3 ,44.9 ,41.6 ,47.5 ,43.7 ,45.3 ,44.1 ,50.2 ,42.3 , 42.2]
plt.plot(x,same_20_40)
plt.xlabel("Time (sec)")
plt.ylabel("Throughput (Mbits/sec)")
plt.xticks([0 , 5 , 10 , 15 , 20 , 25 , 30 ,35 , 40 , 45 ,50 ,55 ,60])
plt.show()
```



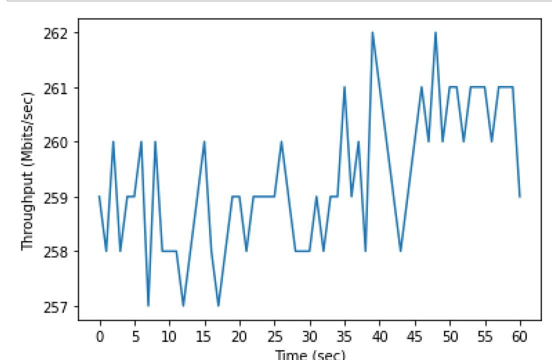


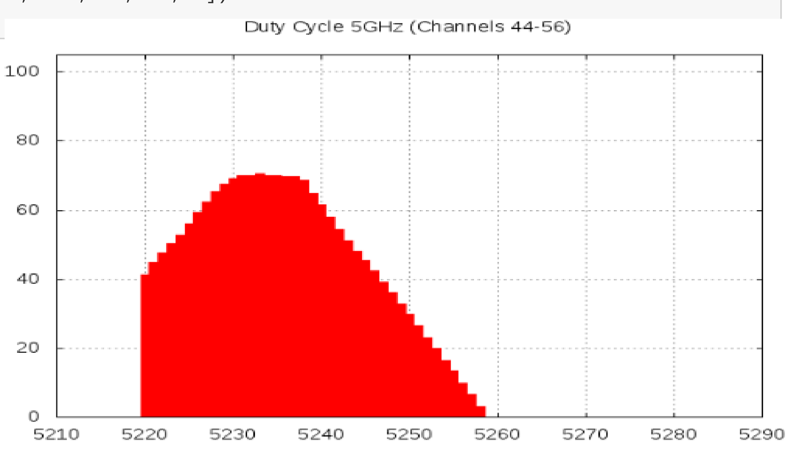
40 Mhz Under Test

40 Mhz link

Best MCS: MCS21 , index: 145 (SGI 3)

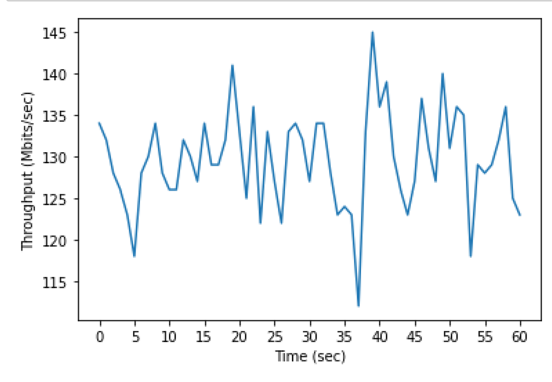
In [6]:
```python
link_40 = [259 ,258 ,260 ,258 ,259 ,259 ,260 ,257 ,260 ,258 ,258 ,258 ,257 ,258 ,259 ,260 ,258 ,257 ,258 ,259 ,259 ,258 ,259 ,259 ,259 ,259 ,260 ,259 ,258 ,258 ,258 ,259 ,258 ,259 ,259 ,261 ,259 ,260 ,258 ,262 ,261 ,260 ,259 ,258 ,259 ,260 ,261 ,260 ,262 ,260 ,261 ,261 ,260 ,261 ,261 ,261 ,260 ,261 ,261 ,261 ,259]
plt.plot(x,link_40)
plt.xlabel("Time (sec)")
plt.ylabel("Throughput (Mbits/sec)")
plt.xticks([0 , 5 , 10 , 15 , 20 , 25 , 30 ,35 , 40 , 45 ,50 ,55 ,60])
plt.show()
```

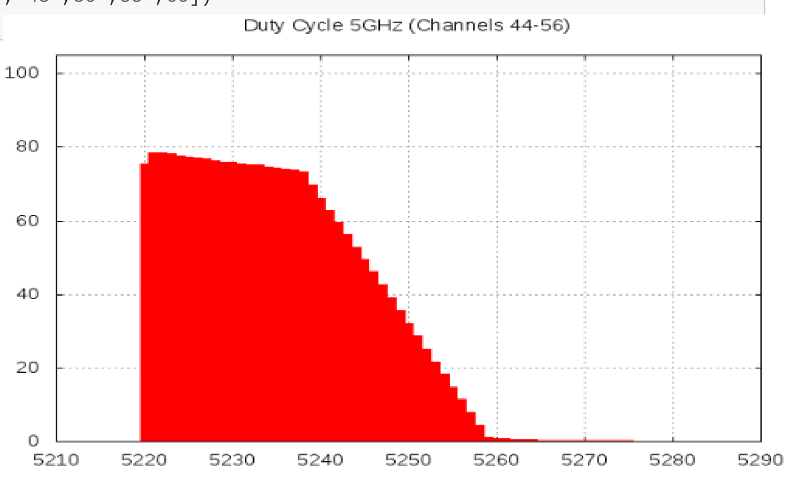




40 Mhz with 40 Mhz adjacent

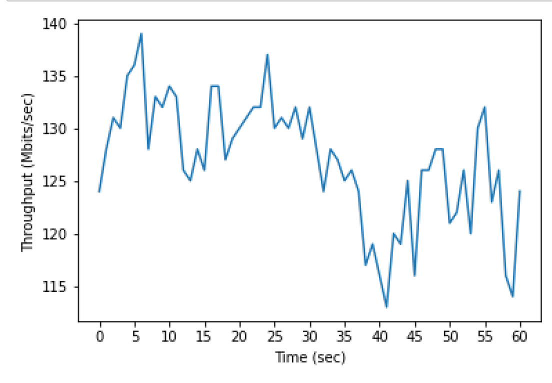
In [7]:
```python
adj_40_40 = [134 ,132 ,128 ,126 ,123 ,118 ,128 ,130 ,134 ,128 ,126 ,126 ,132 ,130 ,127 ,134 ,129 ,129 ,132 ,141 ,133 ,125 ,136 ,122 ,133 ,127 ,122 ,133 ,134 ,132 ,127 ,134 ,134 ,128 ,123 ,124 ,123 ,112 ,133 ,145 ,136 ,139 ,130 ,126 ,123 ,127 ,137 ,131 ,127 ,140 ,131 ,136 ,135 ,118 ,129 ,128 ,129 ,132 ,136 ,125 , 123]
plt.plot(x,adj_40_40)
plt.xlabel("Time (sec)")
plt.ylabel("Throughput (Mbits/sec)")
plt.xticks([0 , 5 , 10 , 15 , 20 , 25 , 30 ,35 , 40 , 45 ,50 ,55 ,60])
plt.show()
```

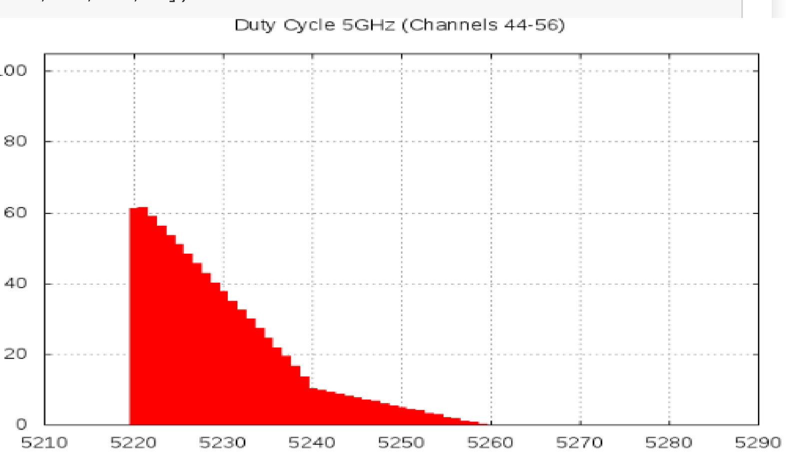




40 Mhz with 20 Mhz adjacent

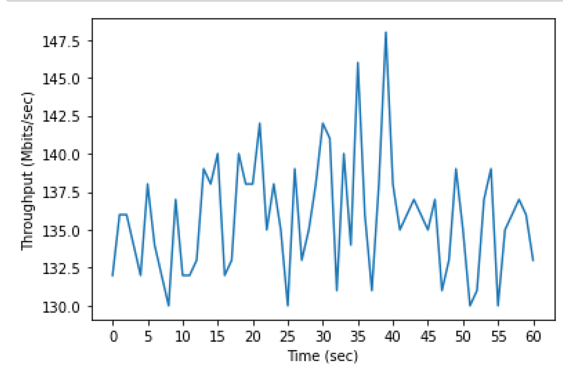
In [8]:
```python
adj_40_20 = [124 ,128 ,131 ,130 ,135 ,136 ,139 ,128 ,133 ,132 ,134 ,133 ,126 ,125 ,128 ,126 ,134 ,134 ,127 ,129 ,130 ,131 ,132 ,137 ,130 ,131 ,130 ,132 ,129 ,132 ,128 ,124 ,128 ,127 ,125 ,126 ,124 ,117 ,119 ,116 ,113 ,120 ,119 ,125 ,116 ,126 ,126 ,128 ,128 ,121 ,122 ,126 ,120 ,130 ,132 ,123 ,126 ,116 ,114 ,124]
plt.plot(x,adj_40_20)
plt.xlabel("Time (sec)")
plt.ylabel("Throughput (Mbits/sec)")
plt.xticks([0 , 5 , 10 , 15 , 20 , 25 , 30 ,35 , 40 , 45 ,50 ,55 ,60])
plt.show()
```

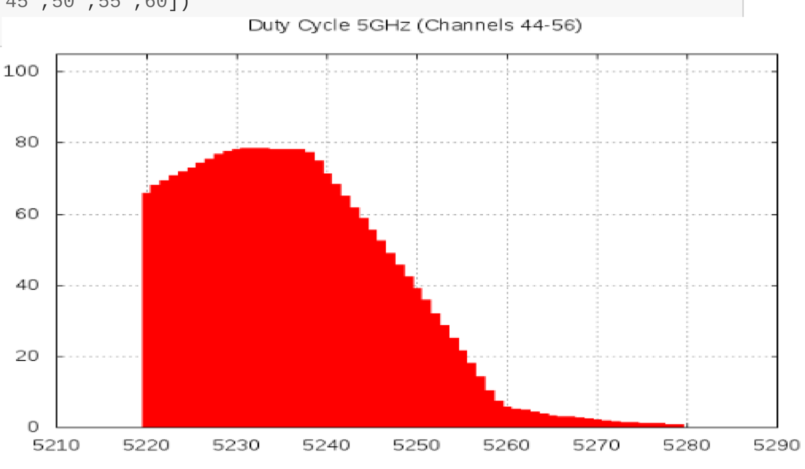




Two 40 Mhz sharing the same channel

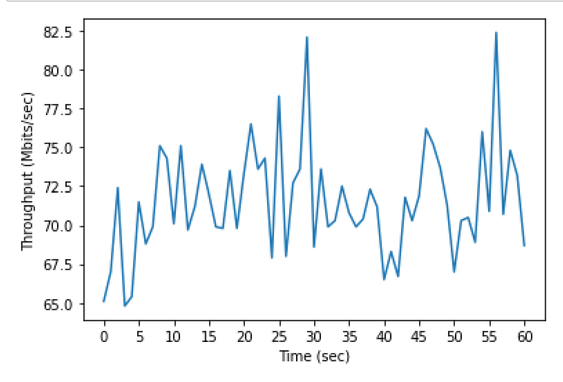
In [9]:
```python
same_40 = [132 ,136 ,136 ,134 ,132 ,138 ,134 ,132 ,130 ,137 ,132 ,132 ,133 ,139 ,138 ,140 ,132 ,133 ,140 ,138 ,138 ,142 ,135 ,138 ,135 ,130 ,139 ,133 ,135 ,138 ,142 ,141 ,131 ,140 ,134 ,146 ,136 ,131 ,138 ,148 ,138 ,135 ,136 ,137 ,136 ,135 ,137 ,131 ,133 ,139 ,135 ,130 ,131 ,137 ,139 ,130 ,135 ,136 ,137 ,136 ,133]
plt.plot(x,same_40)
plt.xlabel("Time (sec)")
plt.ylabel("Throughput (Mbits/sec)")
plt.xticks([0 , 5 , 10 , 15 , 20 , 25 , 30 ,35 , 40 , 45 ,50 ,55 ,60])
plt.show()
```

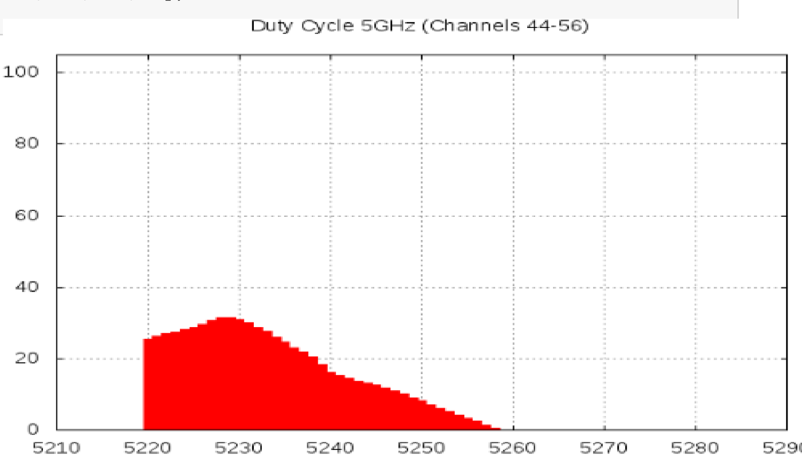




40 Mhz and 20 Mhz sharing the same channel

In [10]:
```python
share_40_20 = [65.1 ,67.0 ,72.4 ,64.8 ,65.4 ,71.5 ,68.8 ,69.9 ,75.1 ,74.3 ,70.1 ,75.1 ,69.7 ,71.2 ,73.9 ,72.0 ,69.9 ,69.8 ,73.5 ,69.8 ,73.3 ,76.5 ,73.6 ,74.3 ,67.9 ,78.3 ,68.0 ,72.7 ,73.6 ,82.1 ,68.6 ,73.6 ,69.9 ,70.3 ,72.5 ,70.8 ,69.9 ,70.4 ,72.3 ,71.2 ,66.5 ,68.3 ,66.7 ,71.8 ,70.3 ,71.9 ,76.2 ,75.2 ,73.7 ,71.3 ,67.0 ,70.3 ,70.5 ,68.9 ,76.0 ,70.9 ,82.4 ,70.7 ,74.8 ,73.2 ,68.7]
plt.plot(x,share_40_20)
plt.xlabel("Time (sec)")
plt.ylabel("Throughput (Mbits/sec)")
plt.xticks([0 , 5 , 10 , 15 , 20 , 25 , 30 ,35 , 40 , 45 ,50 ,55 ,60])
plt.show()
```





General Observations

- **If the interferer operates on an adjacent 20MHz channel (20MHz adj), then channel bonding degrades performance.**
- **If the interferer operates on an adjacent 40MHz channel (40MHz adj), channel bonding improves performance.**
- **If the interfering channel is separated by 20MHz, channel bonding always improves performance.**
- **Our findings on channel sharing show that, regardless of the bandwidth of under test link, it is more advantageous for under test link to compete for the channel with an interferer who transmits at 40MHz: 40MHz interferers attain higher transmission rates and alleviate fairness issues in multi-rate scenarios, leading to better performance**

2.4 GHz Band Experimentation Environment

Scenario: We keep our SUT (system under test) on channel 1 and we slide the interference channel throughout the whole spectrum (channels 1-11). As above, we disable CCA (actually we disable bss neighbor /force 40 MHz channels in hostapd) by changing the src/ap/hw_features.c file from the source code of hostapd to ignore the overlapping BSSes. We actually modify the case where 20/40 MHz operation is not permitted by comment out iface->conf->secondary_channel = 0; DILLIGAF . Then we compiled our new hostapd and run it as executable in the compiled directory: (./hostapd -dd hostapd.conf).

Case(#)	Link 2 Ch (Interf.)	Link 1 Ch width (MHz)	Link 2 Ch width (MHz)	Link 1 Throughput (Mb/s)	Link 2 Throughput (Mb/s)	Duty Cycle File
1	-	20	-	122.0	-	Case1.txt
2	1	20	20	29.8	50.06	Case2.txt
3	1	20	40	60.7	41.4	Case3.txt
4	2	20	20	34.2	49.5	Case4.txt
5	2	20	40	38.6	41.6	Case5.txt
6	3	20	20	58	31.3	Case6.txt
7	3	20	40	39.09	38.3	Case7.txt
8	4	20	20	48.39	38.95	Case8.txt
9	4	20	40	65.04	29.5	Case9.txt
10	5	20	20	61.59	37.55	Case10.txt
11	5	20	40	58.57	31.44	Case11.txt
12	6	20	20	61.8	78.5	Case12.txt
13	6	20	40	70.6	73.04	Case13.txt
14	7	20	20	68.82	80.14	Case14.txt
15	7	20	40	62.45	48.47	Case15.txt
16	8	20	20	72.25	87.77	Case16.txt
17	8	20	40	86.14	80.4	Case17.txt
18	9	20	20	76.87	90.05	Case18.txt
19	9	20	40	77.8	59.2	Case19.txt
20	10	20	20	77.64	89.89	Case20.txt
21	11	20	20	83.3	89.85	Case21.txt
22	-	40	-	124.2	-	Case22.txt
23	1	40	20	42.05	55.96	Case23.txt
24	1	40	40	57.66	41.9	Case24.txt
25	2	40	20	31.72	47.78	Case25.txt
26	2	40	40	41.58	36.02	Case26.txt
27	3	40	20	19.64	65.42	Case27.txt
28	3	40	40	27.6	53.05	Case28.txt
29	4	40	20	57.73	32.42	Case29.txt
30	4	40	40	32.23	56.62	Case30.txt
31	5	40	20	46.73	56.2	Case31.txt
32	5	40	40	61.37	36.58	Case32.txt
33	6	40	20	36.68	80.1	Case33.txt
34	6	40	40	41.75	71.22	Case34.txt
35	7	40	20	41.73	81.11	Case35.txt
36	7	40	40	45.45	45.03	Case36.txt
37	8	40	20	45.52	83.61	Case37.txt
38	8	40	40	48.63	80.4	Case38.txt

39	9	40	20	60.69	85.28	Case39.txt
40	9	40	40	60.8	65.49	Case40.txt
41	10	40	20	98.26	86.61	Case41.txt
42	11	40	20	102.97	85.03	Case42.txt

Conclusion: As expected, the overall performance of channel bonding is significantly worse in the 2.4 GHz band than the one in the 5 GHz. This is proved by the duty cycle measurements as, in this case, the spectrum is much more occupied and not friendly for channel bonding.