Question 1

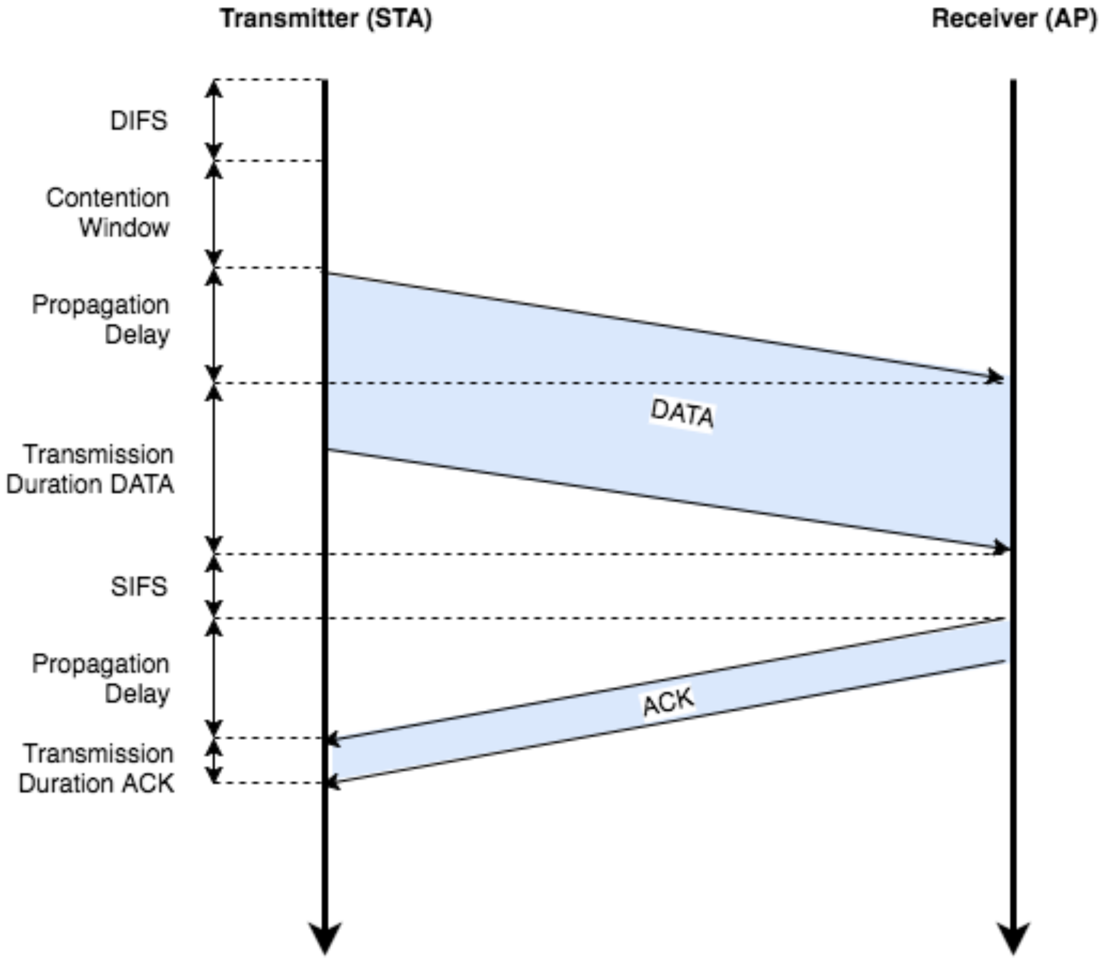
a) Data throughput with and without RTS/CTS

The following figure gives an overview of the data flow from a STA to an AP without using RTS/CLS mechanism. A few general assumptions were made:

- no loss or collsion during transmission
- no interference
- no hidden or exposed terminals
- no fragmentation

Without RTS/CTS

Flow diagram:



Defintions:

- DIFS time: $t_{DIFS} = 34\ \mu s$
- Slot Time: $t_{ST} = 9\ \mu s$
- Maximum backoff slots: $b_{max} = 15$
- Random backoff: $RB = \{n : \text{n is an integer; and } 1 \leq n \leq b_{max}\}$
- Expected backoff: $b_{expt} = \frac{b_{max}+1}{2} = 8$
- Contention window: $t_{CW} = b_{expt} \cdot t_{ST} = 72\ \mu s$
- Propagation delay: $t_{pd} = 1\ \mu s$
- SIFS time: $t_{SIFS} = 16\ \mu s$
- PHY layer overhead = $t_{phy} = 20\ \mu s$
- OFDM symbol duration = $t_{ODFM} = 4\ \mu s$
- MAC layer data payload = $d_{mpay} = 1452\ B$
- MAC header size = $d_{mhead} = 28\ B$
- MAC ack size = $d_{mack} = 14\ B$
- PHY Layer transmission rate: $r = 54 \text{ Mbps} = 7.077888\ \frac{B}{\mu s}$
- Transmission duration data: $t_{data} = t_{phy} + t_{ODFM} + \frac{d_{mhead} + d_{mpay}}{r} \approx 243\ \mu s$

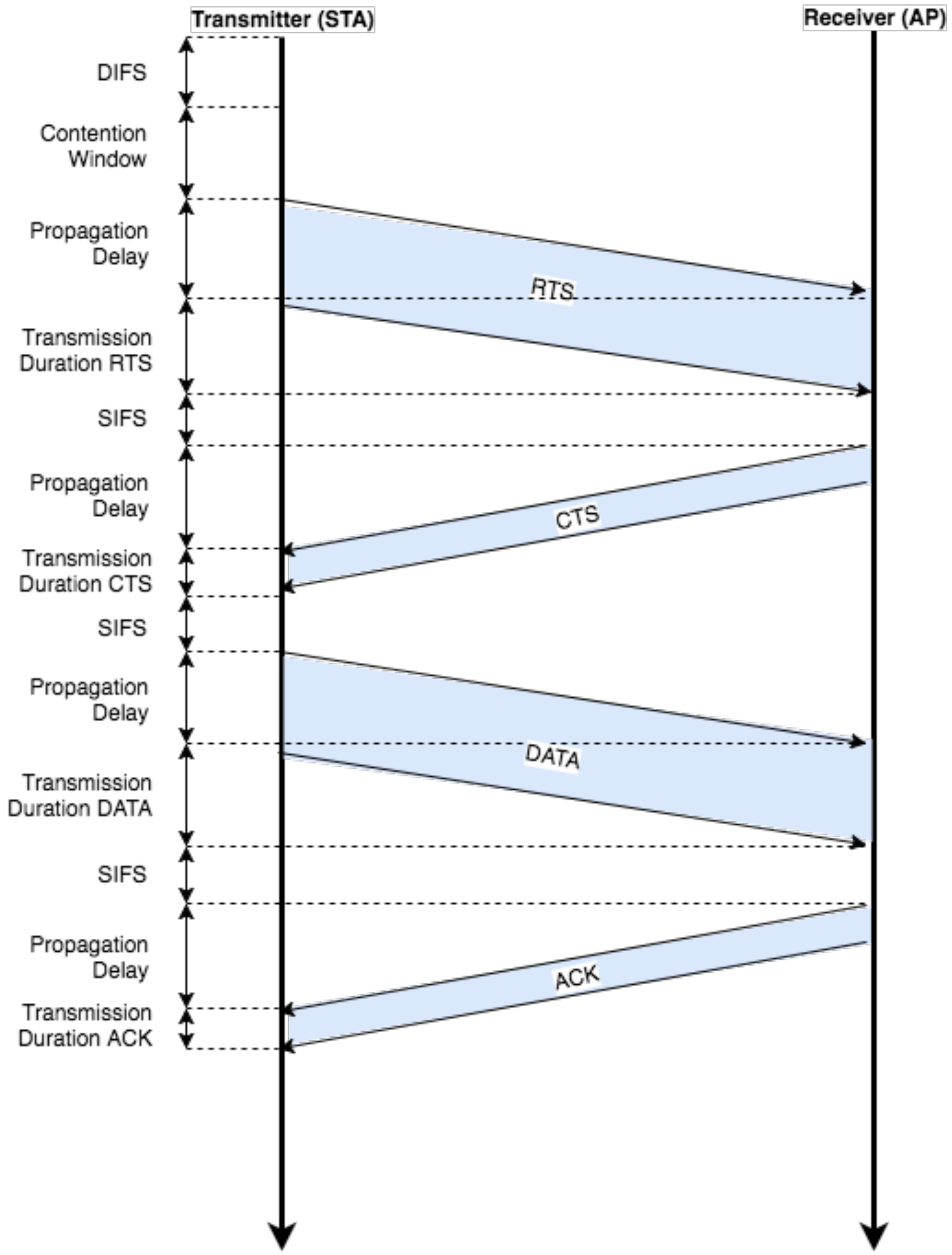
- Transmission duration ack: $t_{ack} = t_{phy} + t_{ODFM} + \frac{d_{mhead} + d_{mack}}{r} \approx 30\ \mu s$
- Total Time: $t_{total} = t_{DIFS} + t_{CW} + 2 \cdot t_{pd} + t_{data} + t_{SIFS} + t_{ack} \approx 397\ \mu s$

Calculated Transmission Rate:

$$r_{act} = \frac{dmpay}{t_{total}} \approx \frac{1452\ B}{397\ \mu s} \approx \frac{1.11 \cdot 10^{-2}\ Mbit}{3.97 \cdot 10^{-4}\ s} \approx 28.0\ \text{Mbps}$$

With RTS/CTS

Flow diagram:



Additional Definitions to the previous:

- CTS size: $d_{cts} = 14\ B$
- RTS size: $d_{rts} = 20\ B$
- Transmission duration CTS: $t_{cts} = t_{phy} + t_{ODFM} + \frac{d_{mhead} + d_{cts}}{r} \approx 30\ \mu s$
- Transmission duration CTS: $t_{cts} = t_{phy} + t_{ODFM} + \frac{d_{mhead} + d_{rts}}{r} \approx 31\ \mu s$
- Total Time: $t_{total} = t_{DIFS} + t_{CW} + 4 \cdot t_{pd} + t_{rts} + t_{cts} + t_{data} + 3 \cdot t_{SIFS} + t_{ack} \approx 493\ \mu s$

Calculated Transmission Rate:

$$r_{act} = \frac{dmpay}{t_{total}} \approx \frac{1452\ B}{493\ \mu s} \approx \frac{1.11 \cdot 10^{-2}\ Mbit}{4.93 \cdot 10^{-4}\ s} \approx 22.5\ \text{Mbps}$$

Conclusion

With RTS/CTS disabled there is a theoretical transmission rate of about 28.0 Mbps. With RTS/CTS enabled it is about 22.5 Mbps. That is 20 % less throughput. The reason are the additional frames for the handshake and the addtional propagation delays and SIFS.

b) Data throughput with and without RTS/CTS

Terminology:

- N6 = Node 6
- N15 = Node 15
- ST = Stepping Stone

Setup

- N6 is set as the AP?

  N6: `iw wlan0 info | grep type`

  Output: `type AP`

- Get N6 IP address N6: `ifconfig wlan0 | grep "inet addr"`

  Output: `inet addr:172.17.5.10 Bcast:172.17.5.255 Mask:255.255.255.0`

- N15 is set as client and connected to AP of N6

  N15: `ping -I wlan0 172.17.5.10`

  Output (trunc): `64 bytes from 172.17.5.10: seq=0 ttl=64 time=0.898 ms`

- Enable RTS/CTS on N15:

N15: `iw phy phy0 set rts 100`

- Set bitrates on both interfaces:

  N15: `iw wlan0 set bitrates legacy-2.4 54.0` N6: `iw wlan0 set bitrates legacy-2.4 54.0`

- Set tx power on client

  N15: `iw wlan0 set txpower fixed 30.0`

- Review settings on client

  N15: `iwinfo`

  Output:

```
wlan0 ESSID: "group06_ap"
      Access Point: 00:1B:B1:07:DB:9B
      Mode: Client  Channel: 11 (2.462 GHz)
      Tx-Power: 30 dBm  Link Quality: 70/70
      Signal: -38 dBm  Noise: -96 dBm
      Bit Rate: 54.0 MBit/s
      Encryption: none
      Type: nl80211  HW Mode(s): 802.11abg
      Hardware: 168C:0013 185F:1012 [Generic MAC80211]
      TX power offset: unknown
      Frequency offset: unknown
      Supports VAPs: yes  PHY name: phy0
```

- Start iperf server

  N6: `iperf -s -u`

- Start client with 1400 B UDP datagrams CTS/RTS Threshold 100 B

```
for i in `seq 10`; do
    iperf -c 172.17.5.10 -u -b 54M -t 30 -l 1400
    sleep 2
done
```

- Start client with 200 B UDP datagrams CTS/RTS Threshold 100 B

```
for i in `seq 10`; do
    iperf -c 172.17.5.10 -u -b 54M -t 30 -l 200
    sleep 2
done
```

- disable CTS/RTS

  N15: `iw phy phy0 set rts off`

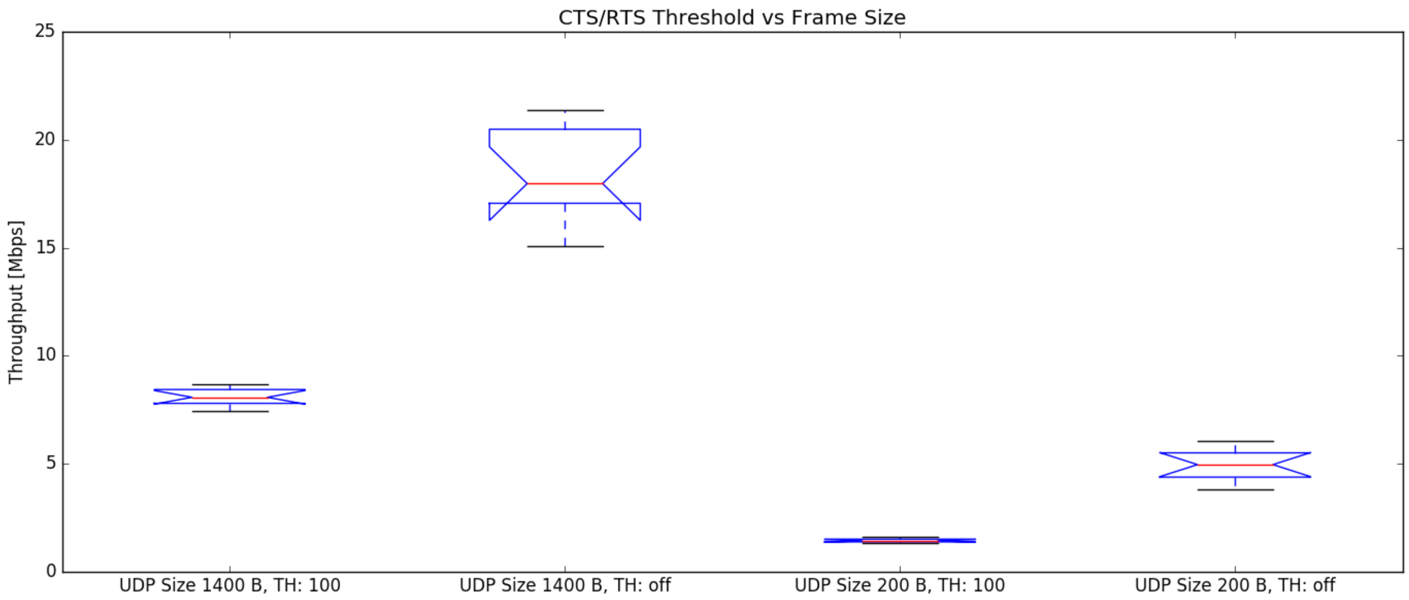
- Start client with 1400 B UDP datagrams CTS/RTS off

```
for i in `seq 10`; do
    iperf -c 172.17.5.10 -u -b 54M -t 30 -l 1400
    sleep 2
done
```

- Start client with 200 B UDP datagrams CTS/RTS off

```
for i in `seq 10`; do
    iperf -c 172.17.5.10 -u -b 54M -t 30 -l 200
    sleep 2
done
```

Boxplots



Conclusion

The figure above shows boxplots from four experiments which are the combinations of CTS/RTS off and on, and UDP Packet Size of 1400 Bytes and 200 Bytes. The UDP data sent is fixed on all experiments (54

Mbps). We expected RTS/CTS enabled to have a smaller throughput with same packet lengths because it introduces additional MAC frames that do not transport actual payload but control the traffic. Also, in theory, RTS/CTS enabled results in a more stable throughput, because it reduced the risk of frame loss due to collisions.

RTS/CTS disabled produce the best throughput respectively on the same UDP size but are also more spread visible at the CIs. Exactly as expected.

What is different from our expectations is the difference between the calculated theoretical and the actual throughput. For UDP with about 1400 B size we calculated 28 Mbps. But we measured around 18 Mbps (-36% less) for CTS/RTS disbaled. With this feature enabled we measured around 8 Mbps (-65% than calculated). In general the actual throughput is less because of other traffic on the medium like beacons and other control and management frames as well as interference.

A possible reason for CTS/RTS-enabled-throughput is even slower (compare percentages in previous paragraph) is that there might be exposed terminals that prevents the client from sending.