How does Carrier Sensing and Interference impact Wi-Fi performance?
A study of 7 cases that manifest in a two cell (2AP-2STA) scenario

Applicable Release: NetSim v13.2.20 or higher
Applicable Version(s): All (Academic, Standard and Pro)
Project download link: See Appendix-1. The URL has the configuration files (scenario, settings, and other related files) of the examples discussed in this analysis for users to import and run in NetSim

Motivation

Wi-Fi networks (or, more formally, IEEE 802.11 Wireless Local Area Networks) are today ubiquitous. Everyone "connects to the Wi-Fi" in homes, offices, hotels, airports, trains and other public places. Sometimes we encounter situations where the signal strength is excellent, but the data rate is low. What causes this? The answer is complicated and requires an understanding of the 802.11 protocol. More specifically, how phenomena known as carrier sense blocking and interference impact WiFi performance. In this paper, we study this (and more) via 802.11g simulations using NetSim.

Researchers can utilize this work (along with NetSim) as a base for exploration in many different directions. These include (i) Analysis for 802.11n and 802.11 ac WLAN networks which use packet aggregation (ii) Varying the transmit power or CS threshold instead of distance (iii) Varying protocol parameters such as CW Min or CW Max (iv) Modifying the layout geometry (v) Increasing the device counts, and so on. The understanding gained will help effectively design, deploy and manage WiFi networks.

Background

The IEEE 802.11 standard provides two modes of operation, namely, the *ad hoc* mode and the *infrastructure* mode. Commercial and enterprise WLANs usually operate in the infrastructure mode. An infrastructure WLAN contains one or more *Access Points (APs)* which provide service to a set of users or *client stations (STAs)*. Every STA in the WLAN associates itself with exactly one AP. Each AP, along with its associated STAs, constitutes a so-called *cell*. Each cell operates on a specific channel. Cells that operate on the same channel are called co-channel. We call a WLAN with multiple APs a *multi-cell WLAN* [1]. Since the number of non-overlapping channels is limited, as the density of APs increase co-channel cells become closer. Nodes (i.e., AP or STA) in two closely located co-channel cells can suppress each other's transmissions via carrier sensing and interfere with each other's receptions causing packet losses.

In single cells, every node can detect the beginning and the end of transmissions by every other node. Thus, nodes in a single cell have the same global view of the activities on the common medium. Moreover, there are no hidden and exposed nodes, and the nodes are synchronized due to the common global view. However, in multi-cell infrastructure WLANs, each node can have a different local view of the activities around itself, and its own activities are determined by this local view. Thus, the evolution of activities of each node needs determines the fraction of time for which each node transmits or senses the medium idle/busy. Also, the interactions among the nodes determines the probability with which (bidirectional exchange of DATA-ACK or RTS-CTS-DATA-ACK) transmissions on a given link are successful.

The 2AP-2STA scenario

Given below is a sketch of the scenario that we study. There are two APs and two STAs placed in a line. APs are at the ends and the STAs in between. The AP-STA distance is d while the AP-AP distance is D; STA-STA distance is therefore $D - 2d$.

Figure 1: A simple 2 cell scenario comprising of 2 APs and 2 STAs. The AP1 and STA1 (and AP2 and STA2) send data to one another over the wireless link L1 (and L2 resp.). The AP-STA separation is d while the AP-AP separation is D.

Since the AP-STA distances for both pairs are equal, AP1-STA2 and AP2-STA1 distances are also equal. Let us assume the traffic generation rates at both APs and both STAs are equal. Then:

- By *pairwise symmetry*, if the traffic rates at both STAs and APs are equal, then *whatever D and d maybe,* and *whatever the underlying WiFi behaviour may be* the STA1-AP1 (long term) performance should be the same as STA2-AP2 performance. Ditto for AP1-STA1 and AP2-STA2 performances.
- On deeper inspection, we see there will be *global symmetry* across all STAs and APs when (i) the pairs are independent (scenario 1 in Figure 4) and (ii) all 4 nodes see carrier sense blocking and interference from one another (scenario 7 in Figure 4). In these cases, the (long term) performance of all 4 devices will be exactly the same

Simulation results, tabulated towards the end of this document, validate this assertion.

Radio Propagation

The radio propagation model is the log-distance model whereby, if a transmitter transmits at power P_T to a receiver at distance D (meters) (where it is assumed that $D > 1$), then the received power is given by:

$$P_R = P_T - 40.09 - 10 \times \eta \times \log_{10}(D)$$

The 40.09 dB loss is at the distance of 1 meter, and this value holds for the 2.4 GHz band. In a 3-dimensional model we have $\eta > 2$; a typical value being $\eta = 2.6$, which we use in the NetSim simulations below. Thus, for example, a transmit power of 100 mW, i.e., 20 dBm, will drop to -20 dBm, or 10^{-2}mW, at the distance of 1 meter, and to -46 dBm at the distance of 10 m.

Carrier Sensing (CS)

In the 802.11 CS mechanism, a wireless station withholds its transmission when it senses an ongoing transmission on the medium. It is a sender side phenomenon unlike interference which is a receive side phenomena. The CS threshold is defined as the min receive sensitivity at the control rate which -82 dBm (users can change CS threshold in NetSim).

MCS Table for 802.11 g

Index	Min Rx Power (dBm)	Modulation	Code Rate	Bit Rate
1	-82	BPSK	$1/2$	6 Mbps
2	-81	BPSK	$3/4$	9 Mbps
3	-79	QPSK	$1/2$	12 Mbps
4	-77	QPSK	$3/4$	18 Mbps
5	-74	16 QAM	$1/2$	24 Mbps
6	-70	16 QAM	$3/4$	36 Mbps
7	-66	64 QAM	$2/3$	48 Mbps
8	-65	64 QAM	$3/4$	54 Mbps

Table 1: 802.11g bit rates for different modulation schemes, and the minimum received signal power and SINR required for achieving each bit rate.

Interference with packet capture

Most WLAN simulators assume that, when two nodes attempt simultaneously in a slot, collision occurs and both attempts fail. In the real world, the power levels of different transmissions as heard at the receiver(s) are different. Hence, it is possible that the receiver can decode a signal with sufficient strength even in the presence of interfering transmissions. i.e., the receiver can capture a frame. This happens when the SINR is sufficiently large. NetSim models frame capture at the receiver as the decoding is based on received SINR. This is explained by means of an example in the next paragraph.

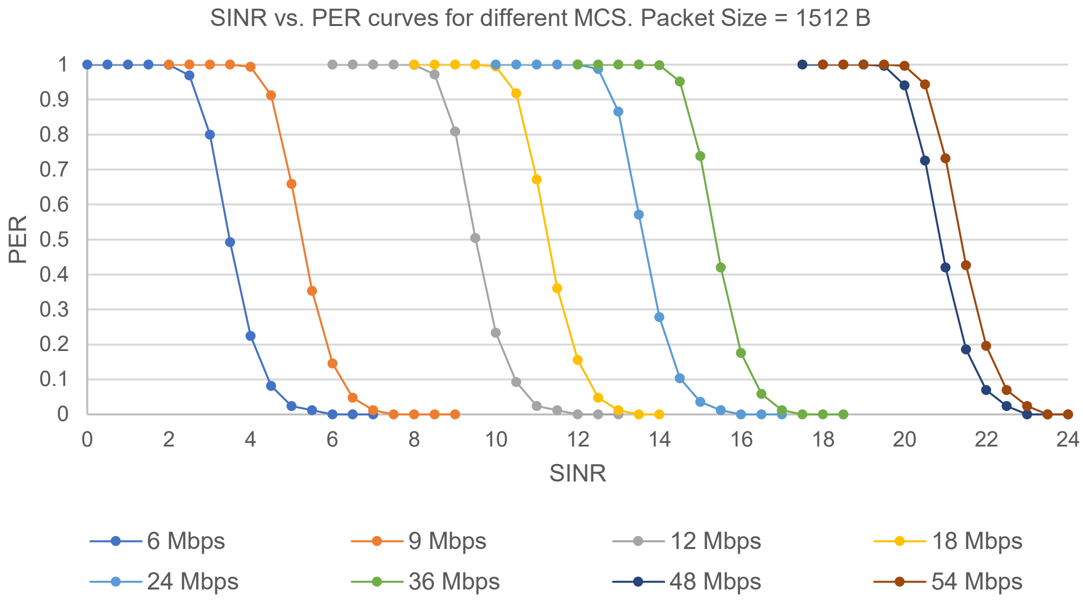


Figure 2: NetSim's 802.11g PER SINR curves for various PHY rates (MCSs). In this paper we use on the right most (54 Mbps) curve. Interference causes packet failure with probability 1 when SINR < 20 dB and packets succeed with probability 1 even with interference when SINR > 21.5 dB.

Let us say AP1 is transmitting to STA1 while STA2 is simultaneously transmitting to AP2. Interference can occur at STA1 i.e., STA2 transmission (to AP2) degrades the SINR at STA1. In the example we are studying the received signal strength at STA1 from AP1 is $-60.20\ dBm$. Hence per Table 1 the PHY rate is 54 Mbps. From Figure 2 we see that packets fail with probability 1 when SINR < 20 dB while packets succeed with probability 1 when SINR > 21.5 dB. So, what is the SINR? This depends on the interfering signal strength from STA2 (at STA1), which in turn depends on the distance between STA1 and STA2. Since the distance varies in the different cases, the SINR also varies. The RSS and SINR calculations for different cases (distances) are shown in Table 2

Before we proceed to the next section, it is important to keep in mind that (i) interference is independent of CS blocking, and (ii) Interference is a receiver side phenomenon while CS blocking is a sender side phenomenon.

The 7 cases that manifest

We notate the distances in the 2AP-2STA cases as shown below. The transmit power is set such that $P^{A1} = P^{A2} = P^{S1} = P^{S2} = 100\ mW$.

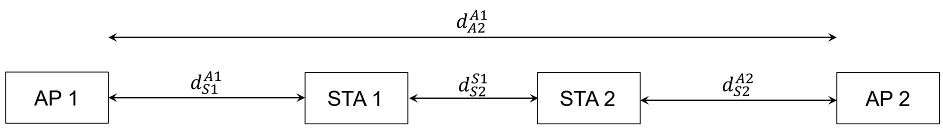


Figure 3: The 2AP-2STA scenario with distances marked. All devices have the same transmit power of 100 mW.

It is remarkable that the change of a single parameter, the distance between the two APs denoted as d_{A2}^{A1}, leads to seven different scenarios as given below. Each of these cases provide rich detail on the impact of CS blocking and interference and merit individual analysis.

We fix $d_{S1}^{A1} = d_{A2}^{S2} = 14m$. Let P_Y^X denote the power received at Y from the source X. Applying the log distance pathloss equation, the power at the receivers are

$$P_{S1}^{A1} = P_{A1}^{S1} = P_{S2}^{A2} = P_{A2}^{S2} = 10 \times \log_{10} 100 - 40.09 - 10 \times 3.5 \times \log(14) = -60.20\ dBm$$

Since $-60.20 > -65$ from Table 1 we see that the PHY rate would be 54 Mbps.

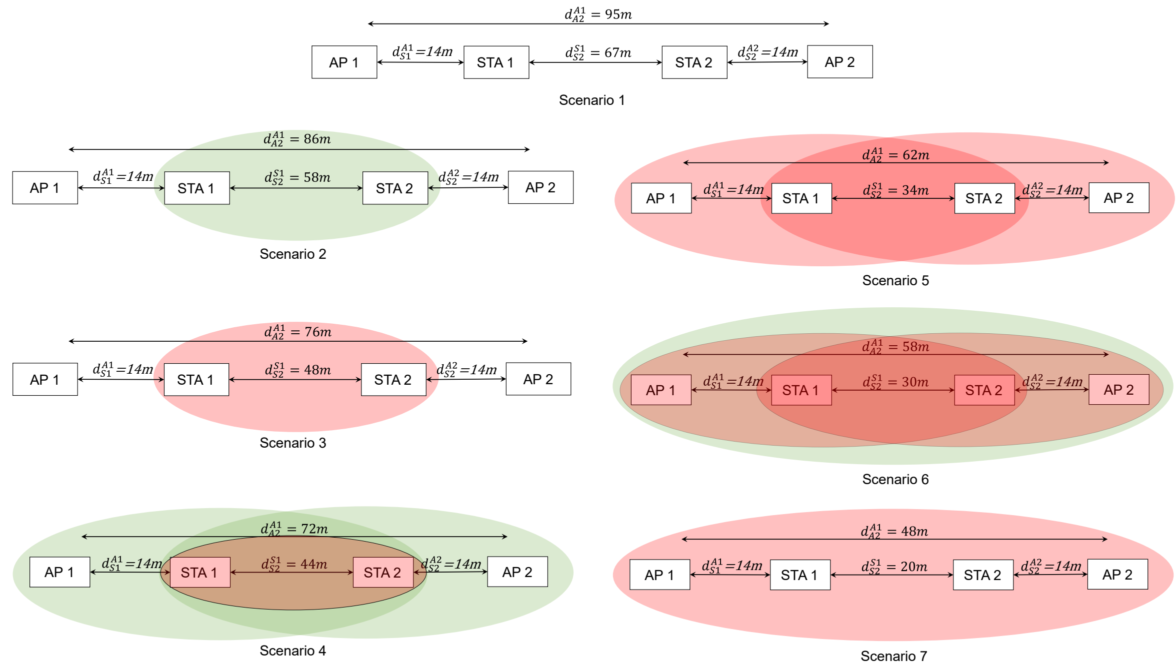


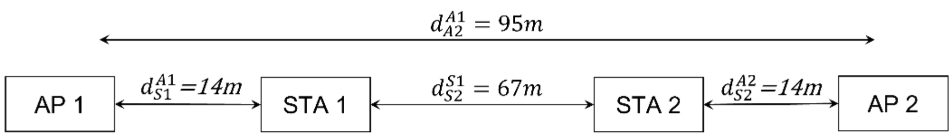
Figure 4: Visual representation of 7 scenarios that manifest in the 2AP-2STA scenario, revealing the intrinsic complexity in multi cell WiFi networks. In all scenarios the distance between each AT-STA pair is 14m. The distance between the APs is varied 48m to 95m. Green colour depicts CS blocking only while red colour means interference and CS blocking. We analyse each these scenarios in detail.

A consolidated table of distances, power and SINR calculations is provided below. Exact computations are explained case wise later in the subsequent sections.

Scenario	d_{A2}^{A1}	d_{S1}^{A1}	d_{S2}^{A1}	P_{S1}^{A1}	PHY Rate	P_{S1}^{S2}	P_{S2}^{A1}	P_{A2}^{A1}	$S1_{A1/S2}^{SINR}$	$S1_{A1/A2}^{SINR}$	$A1_{S1/A2}^{SINR}$
1	95	14	81	-60.20	54	-84.00	-86.88	-89.31	23.79	26.68	29.10
2	86	14	72	-60.20	54	-81.81	-85.09	-87.79	21.60	24.89	27.59
3	76	14	62	-60.20	54	-78.93	-82.82	-85.91	18.72	22.61	25.71
4	72	14	58	-60.20	54	-77.61	-81.81	-85.09	17.40	21.60	24.89
5	62	14	48	-60.20	54	-73.69	-78.93	-82.82	13.48	18.72	22.61
6	58	14	44	-60.20	54	-71.78	-77.61	-81.81	11.58	17.40	21.60
7	48	14	34	-60.20	54	-65.62	-73.69	-78.93	5.42	13.48	18.72

Table 2: Consolidated table of distances, PHY Rate, received powers and SINRs for all scenarios. The blue colour for -81.81 dBm is an indication of breach of CS threshold leading to CS blocking. The green colour for 21.60 dB is the lowest SINR without interference while 18.72 dB is the highest SINR with interference. Notation $S1_{A1/S2}^{SINR}$ means SINR at S1 with desired signal from A1 and interfering signal from S2. Units: Power levels in dBm, SINR in dB and PHY rate in Mbps

Case 1: The STA-AP pairs are independent



Scenario 1

Power at STA1 due to STA2

$$P_{S1}^{S2} = 10\log_{10}(P^{S2}) - 40.09 - 35\log_{10}(d_{S1}^{S2}) = 10\log_{10}(100) - 40.09 - 35\log_{10}(67) = -84\ dBm$$

Since P_{S1}^{S2} is less than $-82\ dBm$ the two STAs are not in carrier sense range. Next, we compute the received power at STA1 from AP1.

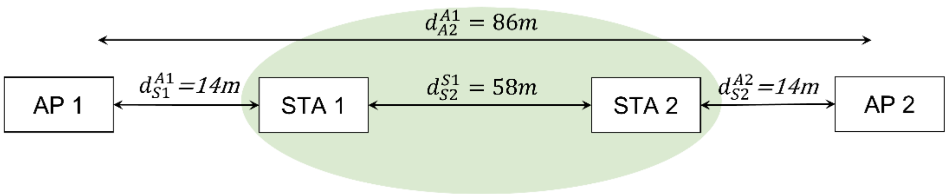
$$P_{S1}^{A1} = 10\log_{10}(P^{A1}) - 40.09 - 35\log_{10}(d_{S1}^{A1}) = -60.20\ dBm$$

At this received power, we see from the tables that the PHY rate is 54 Mbps. Assuming interference is much higher than noise, the SINR at S1 would be

$$S1_{A1/S2}^{SINR} = P_{S1}^{A1} - P_{S1}^{S2} = 23.80\ dB$$

From the SINR tables we see that the SINR threshold for successfully decoding at PHY rate of 54 Mbps is $21.5\ dB$. The SINR at S1 is above this threshold. We thus see the realization of scenario 1, with each AP-STA being independent. This is a 2 node Bianchi [2], [3] case since the STA-AP pairs are spatially separated.

Case 2: STA1 and STA2 are in carrier sense range



Scenario 2

Power at STA1 due to STA2

$$P_{S1}^{S2} = 10\log_{10}(P^{S2}) - 40.09 - 35\log_{10}(d_{S1}^{S2}) = 10\log_{10}(100) - 40.09 - 35\log_{10}(58) = -81.81\ dBm$$

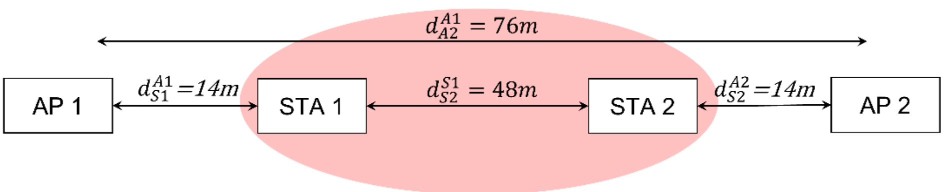
Since P_{S1}^{S2} is greater than $-82\ dBm$ the two STAs are in carrier sense range. The received power at STA1 from AP1 will remain same per case 1, i.e., $-60.20\ dBm$, since the distance between STA1 and AP1 is fixed to 14m.

At this received power, we see from the tables that the PHY rate is 54 Mbps. Assuming interference is much higher than noise, the SINR at S1 is

$$S1_{A1/S2}^{SINR} = P_{S1}^{A1} - P_{S1}^{S2} = 21.61\ dB$$

From the SINR tables we see that the SINR threshold for successfully decoding at PHY rate of 54 Mbps is $21.5\ dB$. The SINR at S1 is above this threshold. Hence there is not interference. We thus see the realization of scenario 2, with STAs in carrier sense range.

Case 3: STA1 and STA2 are in interference range



Scenario 3

It is implicit that STA1 and STA2 will be in CS range.

Now, power at STA1 due to STA2

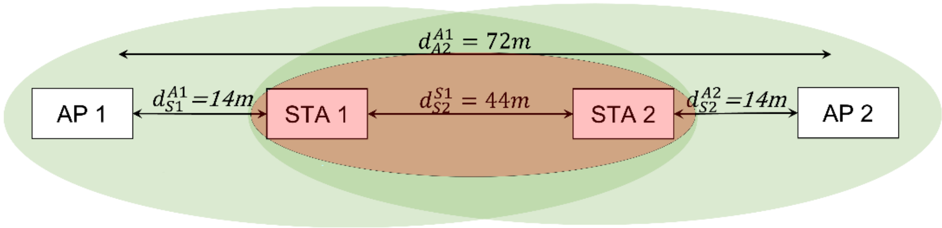
$$P_{S1}^{S2} = 10\log_{10}(P^{S2}) - 40.09 - 35\log_{10}(d_{S1}^{S2}) = 10\log_{10}(100) - 40.09 - 35\log_{10}(48) = -78.93\ dBm$$

Since P_{S1}^{S2} is greater than $-82\ dBm$ the two STAs are in carrier sense range. At this received power, we see from the tables that the PHY rate is 54 Mbps. Assuming interference is much higher than noise, the SINR at S1 (A1 is the transmitter and S2 is the interferer) is

$$S1_{A1/S2}^{SINR} = P_{S1}^{A1} - P_{S1}^{S2} = 18.73\ dB$$

From the SINR tables we see that the SINR threshold for decoding packets with probability 0 for PHY rate of 54 Mbps is $19.5\ dB$. The SINR at S1 is below this threshold. We thus see the realization of scenario 3, with STAs in interference range.

Case 4: AP1 - STA2 and AP2 – STA 1 are in carrier sense range



Scenario 4

It is implicit that STA1 and STA2 will be in interference range and CS range.

Now, power at AP1 due to STA2

$$P_{A1}^{S2} = 10\log_{10}(P^{S2}) - 40.09 - 35\log_{10}(d_{A1}^{S2}) = 10\log_{10}(100) - 40.09 - 35\log_{10}(58) = -81.81\ dBm$$

Since P_{A1}^{S2} is greater than $-82\ dBm$ the pair AP1-STA2 and AP2-STA1 are in carrier sense range.

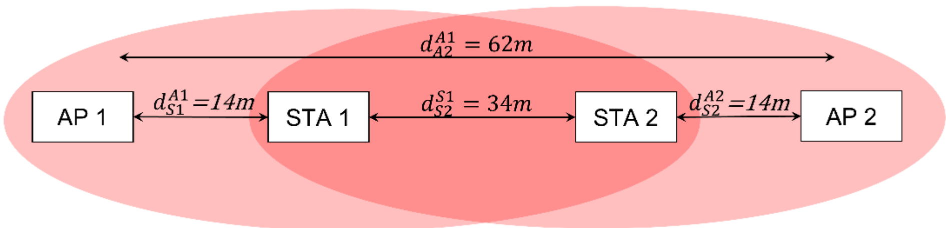
At this received power, we see from the tables that the PHY rate is 54 Mbps. Assuming interference is much higher than noise, the SINR at S1 (A1 is the transmitter and A2 is the interferer) is

$$S1_{A1\,/\,A2}^{SINR} = P_{S1}^{A1} - P_{A1}^{S2} = 21.61\ dB$$

From the SINR tables we see that the SINR threshold for successfully decoding at PHY rate of 54 Mbps is $21.5\ dB$. The SINR due to A2 (and A1) at S1 (and S2 resp.) is above this threshold. S1 and S2 continue to be in interference range.

We thus see the realization of scenario 4, with AP1-STA2 in carrier sense range.

Case 5: AP1 - STA2 and AP2 – STA 1 are in interference range



Scenario 5

It is implicit that STA1 and STA2 will be in interference range and CS range, and that AP1-STA2 and AP2-STA1 will be in CS range.

Now, power at AP1 due to STA2

$$P_{A1}^{S2} = 10\log_{10}(P^{S2}) - 40.09 - 35\log_{10}(d_{A1}^{S2}) = 10\log_{10}(100) - 40.09 - 35\log_{10}(48) = -78.93\ dBm$$

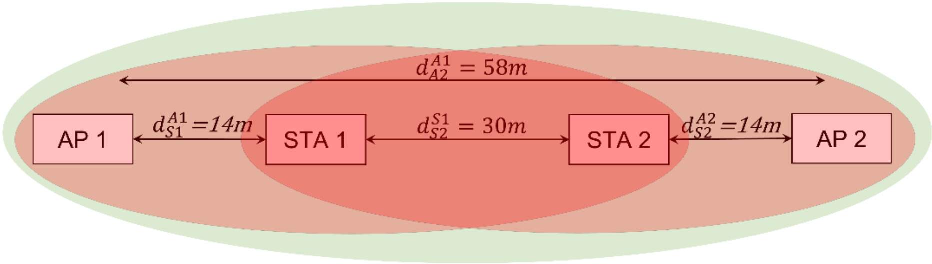
Since P_{A1}^{S2} is greater than $-82\ dBm$ the pair of AP1-STA2 and AP2-STA1 are in interference range.

At this received power, we see from the tables that the PHY rate is 54 Mbps. Assuming interference is much higher than noise, the SINR at S1 (A1 is the transmitter and A2 is the interferer) is

$$S1_{A1/A2}^{SINR} = P_{S1}^{A1} - P_{A1}^{S2} = 18.73\ dB$$

From the SINR tables we see that the SINR threshold for successfully decoding at PHY rate of 54 Mbps is $21.5\ dB$. The SINR at A1 is below this threshold. We thus see the realization of scenario 5, with AP1-STA2 in interference range.

Case 6: AP1 and AP2 are in carrier sense range



Scenario 6

It is implicit that STA1 and STA2 will be in interference range and CS range, and that AP1-STA2 and AP2-STA1 will be in interference range and CS range.

Power at AP1 due to AP2

$$P_{A1}^{A2} = 10\log_{10}(P^{A2}) - 40.09 - 35\log_{10}(d_{A1}^{A2}) = 10\log_{10}(100) - 40.09 - 35\log_{10}(58) = -81.81\ dBm$$

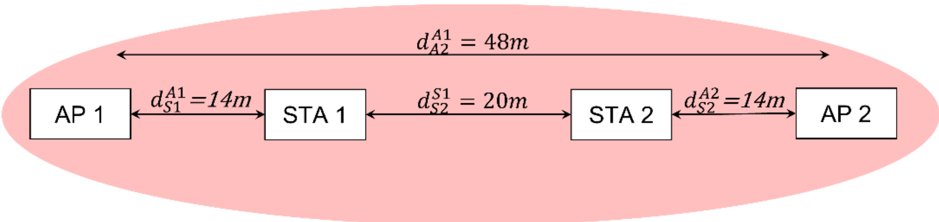
Since P_{A1}^{A2} is greater than $-82\ dBm$ the pair AP1-AP2 are in carrier sense range.

At this received power, we see from the tables that the PHY rate is 54 Mbps. Assuming interference is much higher than noise, the SINR at A1 (S1 is the transmitter and A2 is the interferer) is

$$A1_{S1/A2}^{SINR} = P_{S1}^{A1} - P_{A1}^{A2} = 21.61\ dB$$

From the SINR tables we see that the SINR threshold for successfully decoding at PHY rate of 54 Mbps is $21.5\ dB$. The SINR at A1 or A2 is above this threshold. We thus see the realization of scenario 6, with AP1 and AP2 in carrier sense range.

Case 7: AP1 and AP2 are in interference range



Scenario 7

It is implicit that STA1 and STA2 will be in interference range and CS range, that AP1-STA2 and AP2-STA1 will be in interference range and CS range, and that AP1 and AP2 will be in CS range.

Power at AP1 due to AP2

$$P_{A1}^{A2} = 10\log_{10}(P^{A2}) - 40.09 - 35\log_{10}(d_{A1}^{A2}) = 10\log_{10}(100) - 40.09 - 35\log_{10}(48) = -78.93\ dBm$$

Since P_{A1}^{A2} is greater than $-82\ dBm$ the AP1 and AP2 are in interference range.

At this received power, we see from the tables that the PHY rate is 54 Mbps. Assuming interference is much higher than noise, SINR at A1 (S1 is the transmitter and A2 is the interferer) is

$$A1_{S1/A2}^{SINR} = P_{S1}^{A1} - P_{A1}^{A2} = 18.73\ dB$$

From the SINR tables we see that the SINR threshold for successfully decoding at PHY rate of 54 Mbps is $21.5\ dB$. The SINR at A1 is below this threshold. We thus see the realization of scenario 7, with AP1 and AP2 in interference range.

Basic Access and RTS/CTS [2]

In the 802.11 protocol, the fundamental mechanism to access the medium is called distributed coordination function (DCF). We briefly explain the DCF working below; a detailed explanation can be found in any standard WiFi textbook. DCF employs a random-access scheme, based on the carrier sense multiple access with collision avoidance (CSMA/CA) protocol. Retransmission of collided packets is managed according to binary exponential backoff rules. DCF describes two techniques to employ for packet transmission.

Basic Access: The default scheme is a two-way handshaking technique called basic access mechanism. This mechanism is characterized by the immediate transmission of a positive acknowledgement (ACK) by the destination station, upon successful reception of a packet transmitted by the sender station. Explicit transmission of an ACK is required since, in the wireless medium, a transmitter cannot determine if a packet is successfully received by listening to its own transmission.

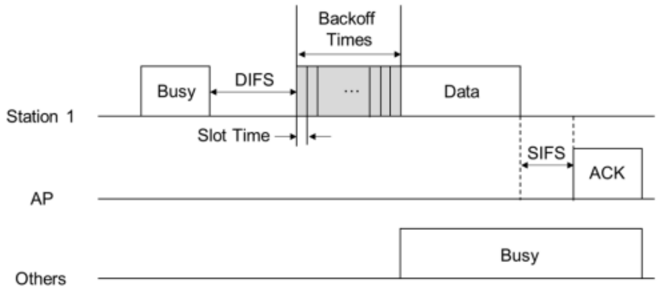


Figure 5: Basic access operation

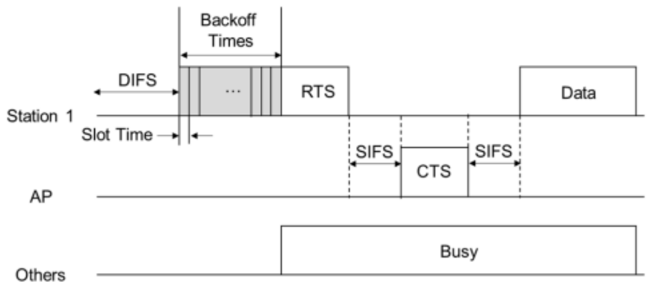


Figure 6: RTS/CTS operation

RTS/CTS Mechanism: In addition to the basic access, an optional four way handshaking technique, known as request-to-send/clear-to-send (RTS/CTS) mechanism has been standardized. Before transmitting a packet, a station operating in RTS/CTS mode “reserves” the channel by sending a special Request-To-Send short frame. The destination station acknowledges the receipt of an RTS frame by sending back a Clear-To-Send frame, after which normal packet transmission and ACK response occurs. Since collision may occur only on the RTS frame, and it is detected by the lack of CTS response, the RTS/CTS mechanism allows to increase the system performance by reducing the duration of a collision when long messages are transmitted. As an important side effect, the RTS/CTS scheme designed in the 802.11 protocol is suited to combat the so-called problem of Hidden Terminals, which occurs when pairs of nodes are unable to hear each other

Traffic Model

In these examples we use a full buffer traffic model with constant packet size 1460B. This means that nodes always have packets to transmit, i.e., all the transmission queues are saturated. AP1 and STA1 transmit data to each other; similarly, AP2 and STA2 transmit data to each other. UDP protocol runs in the transport layer.

Simulation Parameters

MAC layer parameters	
Standard	IEEE802.11g
Operating Frequency	2.4GHz
Rate (MCS) selection	False. Auto rate fall back
RTS Threshold	3000bytes for BA cases 1000bytes for RTS/CTS cases
Frequency Band	2.4GHz
Bandwidth	20MHz
Transmitter Power	100mW for both APs and both STAs
Medium Access Protocol	DCF
Propagation Model	
Channel Model	Path Loss Only (No shadowing or fading)
Path Loss Model	Log Distance
Pathloss Exponent (η)	3.5
Traffic Model	
Packet Size	1460 B
Packet Distribution	Constant
Inter packet arrival time	200 μs (leads to full buffer or infinite backlog)
Other parameters	
Transport Protocol	UDP
Simulation Time	10 seconds

Table 3: Simulation Properties

Results

Part 1 Basic Access (without RTS/CTS)

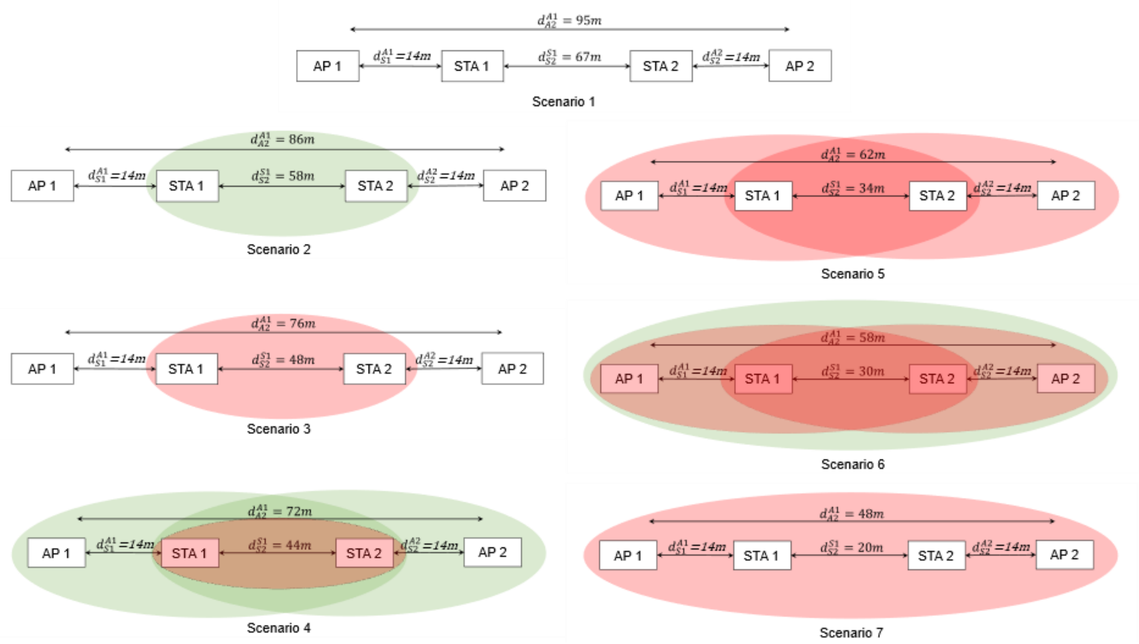


Figure 7: All scenarios are reproduced here again for ease of referencing when reading the results and discussions. Green is CS blocking while Red is interference and CS blocking.

d_{AP2}^{AP1}	Scenario	Description	Throughput (Mbps)			
			A1-S1	S1-A1	A2-S2	S2-A2
95	1	Bianchi	14.40	14.50	14.42	14.48
86	2	S1S2 - CS	19.80	9.44	19.61	9.57
76	3	S1S2 - IF Range	0.10	16.73	0.09	16.75
72	4	A1S2 - CS	8.05	8.94	7.10	9.14
62	5	A1S2 - IF Range	3.75	9.78	3.64	9.77
58	6	A1A2 - CS	6.63	8.28	6.19	8.14
48	7	A1A2 - IF Range	7.35	7.03	7.04	6.76

Table 4: Basic access simulation results - Throughput

In the table below, aggregated AP-STA and STA-AP results are provided as packets per second and packet fail probability. These metrics allow for easy comparison against Markov model (DTMC or CTMC) models built using the Bianchi [3] approach.

Scenario	Description	Pkts/s and pkt fail probability			
		AP-STA		STA-AP	
		Pkts/s	Pkt fail Prob	Pkts/sec	Pkt fail Prob
1	Bianchi	1231.55	0.13	1241.21	0.13
2	S1S2 - CS Range	1684.57	0.06	816.07	0.11
3	S1S2 - IF Range	8.5	0.97	1433.26	0.002
4	A1S2 - CS Range	641.51	0.28	779.50	0.05
5	A1S2 - IF Range	316.21	0.49	836.95	0.13
6	A1A2 - CS Range	549	0.25	703.01	0.19
7	A1A2 - IF Range	508.37	0.24	507.025	0.24

Table 5: Basic access results: Throughput in Packets/sec and Packet Fail Probability

Discussion

- Scenario 1: There are no hidden node collisions, only simultaneous attempt collisions. This is essentially a 2 node Bianchi model.
- Scenario 2: There are no hidden node collisions, only simultaneous attempt collisions. Since AP1 and AP2 can transmit together without mutual interference, their transmissions overlap and they can each get more airtime than STA1 and STA2. In terms of simultaneous collision probabilities, the explanation can be as follows. Let us consider only simultaneous attempts in pairs. For any such pair of simultaneous attempts, either the transmissions of both nodes succeed, or both fails. Thus, the number of failures of all the nodes is the same. But the APs attempt more often, since the STAs block each other, hence their collision probabilities are smaller. This becomes a nice example of an exposed node problem.
- Scenario 3: In this case the transmissions from AP1 and AP2 fail due to hidden node collisions from STA1 or STA2, respectively. This reduces the attempt rates of these nodes, resulting in lower attempt rates, thus giving more airtime to STA1 and STA2.
- Scenario 4: There are no hidden node collisions, since AP1 and AP2 are the only ones that do not mutually CS block, but they also do not interfere with each other's receivers. Consider pairs of simultaneous attempts. When AP1 and STA2 or STA1 and AP2 attempt, there is asymmetry; in each case the AP fails, whereas the STA attempt succeeds. This leads to the difference in the collision probabilities observed.
- Scenario 5: AP1 and AP2 interfere with each other's receivers. Since they can attempt successively, this causes hidden node collisions to AP1 and AP2 transmissions. On the other hand, the STAs do not experience hidden node collisions. The small collision probability that the STAs see is due to simultaneous attempts with nodes that they would have CS blocked.
- Scenario 6: If only hidden node collisions are considered, the problem is completely symmetric. There would no hidden node collisions, and all nodes get the same throughput. Asymmetry arises when we consider simultaneous attempt collisions. Notice that if STA2 and AP1 attempt together, the AP1 attempt will fail, whereas the STA2 attempt will succeed. This is the reason for the slightly lower collision probability for STA2 and STA3.
- Scenario 7: There are no hidden node collisions, only simultaneous attempt collisions. This is essentially a 4 node Bianchi model.

Part 2: RTS/CTS enabled

Understanding the RTS/CTS CS blocking problem [4] – illustrated in the figure below - is essential for a discussion of the results in the RTS/CTS cases.

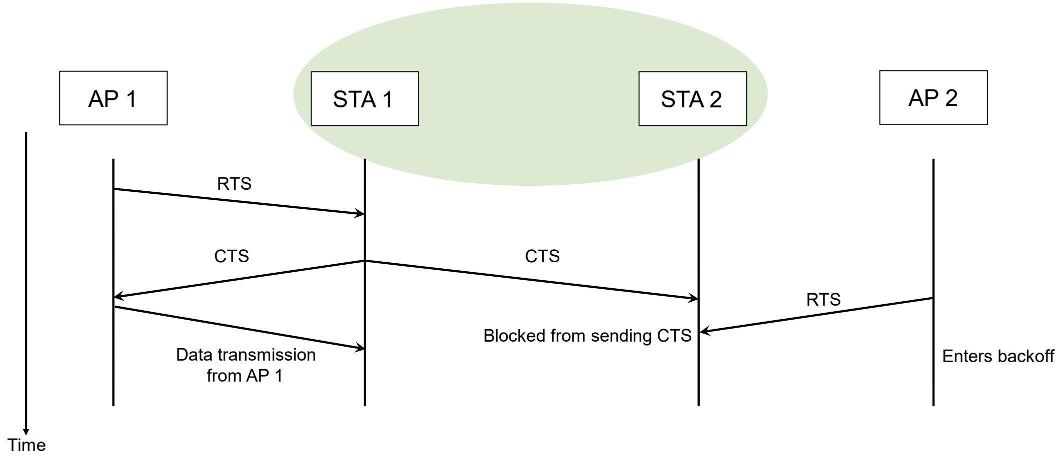


Figure 8: Understanding the CS blocking problem with scenario 2 as an example

A node is CS blocked if it is prohibited from transmitting at a given instant. Since only one node is allowed to transmit at any time within the range of a receiver, other nodes in a wireless network may be blocked. Moreover, neighbours of a blocked node are unaware of the fact that this node is blocked. Therefore, a node may wish to initiate a communication with a node that is presently blocked. In that case, when the sender sends an RTS packet, the destination does not respond because it is blocked. The sender, however, interprets this to be a channel contention and enters backoff. We refer to this problem as the blocking problem.

Consider Scenario 2. In this Figure 8, AP1 transmits an RTS to STA1. STA1 then responds with a CTS. The CTS is heard by STA2. Now when AP2 sends an RTS to STA2. Since STA2 is blocked, it cannot respond with a CTS. AP2, not receiving a CTS, enters into backoff. Thus, there can be no communication between AP2 and STA2 while there is ongoing communication between AP1 and STA1.

In this part we obtain results by enabling of RTS/CTS mechanism.

d_{AP2}^{AP1}	Scenario	Description	Throughput (Mbps)			
			A1-S1	S1-A1	A2-S2	S2-A2
95	1	Bianchi	11.479	11.542	11.462	11.530
86	2	S1S2 - CS Range	6.571	5.477	6.629	5.576
76	3	S1S2 - IF Range	6.015	5.650	6.047	5.766
72	4	A1S2 - CS Range	5.721	5.552	5.617	5.406
62	5	A1S2 - IF Range	5.713	5.591	5.484	5.418
58	6	A1A2 - CS Range	5.956	5.905	5.919	5.939
48	7	A1A2 - IF Range	5.956	5.905	5.919	5.939

Table 6: RTS-CTS simulation results - Throughput

Scenario	Description	AP-STA			STA-AP		
		Pkts/s	Data pkt Fail prob	Ctrl pkt Fail prob	Pkts/s	Data pkt fail prob	Ctrl pkt Fail prob
1	Bianchi	982.07	0	0.129	987.65	0	0.128
2	S1S2 - CS Range	565.06	0	0.064	473.13	0	0.126
3	S1S2 - IF Range	516.33	0.054	0.062	488.67	0	0.115
4	A1S2 - CS Range	485.37	0	0.106	469.05	0	0.128
5	A1S2 - IF Range	479.34	0.01	0.102	471.28	0	0.122
6	A1A2 - CS Range	508.37	0	0.128	507.02	0	0.128

7	A1A2 - IF Range	508.37	0	0.128	507.02	0	0.128

Table 7: RTS-CTS results- Packets/seconds and Packet Fail Probability

The computation formulae used to get the numbers in the above table are

$$prob_{Fail}^{pkt} = \frac{\left(\Sigma Pkt_{error}^{src} + \Sigma Pkt_{collided}^{src} + \Sigma ACK_{error}^{dest} + \Sigma ACK_{collision}^{dest}\right)}{\Sigma Pkt_{transmit}^{src}}$$

$$prob_{Fail}^{ctrl} = prob_{Fail}^{RTS} = \frac{\left(\Sigma RTS_{error}^{src} + \Sigma RTS_{collided}^{src} + \Sigma CTS_{error}^{dest} + \Sigma CTS_{collision}^{dest}\right)}{\Sigma RTS_{transmit}^{src}} = 1 - \frac{CTS_{succ}^{dest}}{RTS_{transmit}^{src}}$$

Discussion

- Scenario 1: Each AP-STA is independent. In either BA or RTS/CTS essentially only one node in each pair attempts successfully. In this 2-node Bianchi model, the lower throughput for RTS-CTS (as compared to BA) is due to the RTS-CTS overhead.
- Scenarios 2 and 3: In the case Basic Access, AP to STA transmissions experience hidden node collisions from attempts by the other STA, leading to dropping of the AP attempt rates, and low AP-STA throughputs. With RTS-CTS, when an AP-STA transmission starts, the other STA is blocked. Since the other AP is also "virtually" blocked then, essentially, all nodes attempt at the same rate and get roughly equal throughputs. The small difference in throughputs is due to simultaneous attempts and MAC-ACK collisions, which are low probability events. Interested users can analyse the packet trace to understand these second order factors.
- Scenario 4 and 5: With RTS-CTS, an attempt by either AP or STA blocks all other transmitters, leading to a fair airtime allocation across the nodes.
- Scenario 6: With BA simultaneous attempts of an STA and the other AP, results in the AP's attempt failing, and its attempt rate reducing, thereby giving more opportunities to the STAs to attempt. In RTS/CTS mode this becomes scenario 7.
- Scenario 7: In either BA or RTS/CTS essentially only one node attempts successfully. As mentioned earlier this is a 4-node Bianchi model. The lower throughput for RTS-CTS is due to the RTS-CTS overhead.

Utility function and comparison of Basic Access vs. RTS/CTS

We use a network utility function – the sum of the logarithms of the node throughputs - to evaluate the network performance. It is a well-known function that balances rate maximization and fairness.

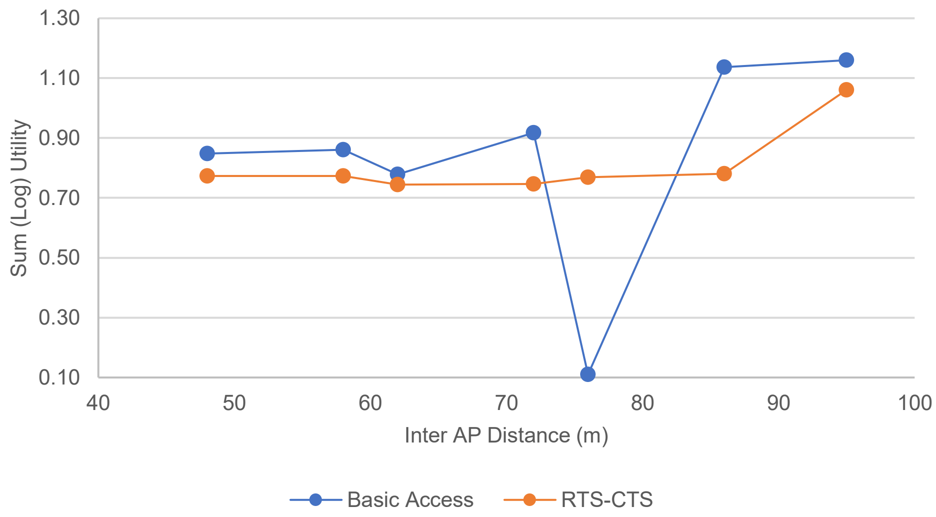


Figure 9: Utility value vs. Inter AP distance for Basic access and RTS/CTS modes. In all cases the AP-STA distance is 14m.

BA outperforms RTS/CTS in 6 cases out of 7. However, in one case (scenario # 3) RTS/CTS is one order of magnitude better than BA. In this scenario, in BA, the AP-STA transmissions are almost zero due to interference from an AP to the STA associated with the other AP. Since the APs are not in CS range, in the BA mode, after one AP starts transmission, the other can starts its transmission as well, resulting in each AP interfering with the other's STA, thereby corrupting each other's transmission. This results in a high loss probability at the APs, and a sharp drop in their attempt rates. In the other 6 cases the RTS/CTS CS blocking problem coupled with the additional load of RTS and CTS frame transmissions outweigh the RTS/CTS benefits. It may be noted that, due to the many cases in which BA actually gives better performance than RTS/CTS, manufacturers limit the use of RTS/CTS.

References

[1] M. Panda and A. Kumar, "Cell-level modeling of IEEE 802.11 WLANs," *Elsevier Ad Hoc Networks,* vol. 25, pp. 84 - 101, 2015.

[2] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun,* vol. 18, no. 3, pp. 535-547, 2000.

[3] A. Kumar, E. Altman, D. Miorandi and M. Goyal, "New insights from a fixed-point analysis of single cell IEEE 802.11 WLANs," *IEEE/ACM Trans. Netw,* vol. 15, no. 3, pp. 588-601, 2007.

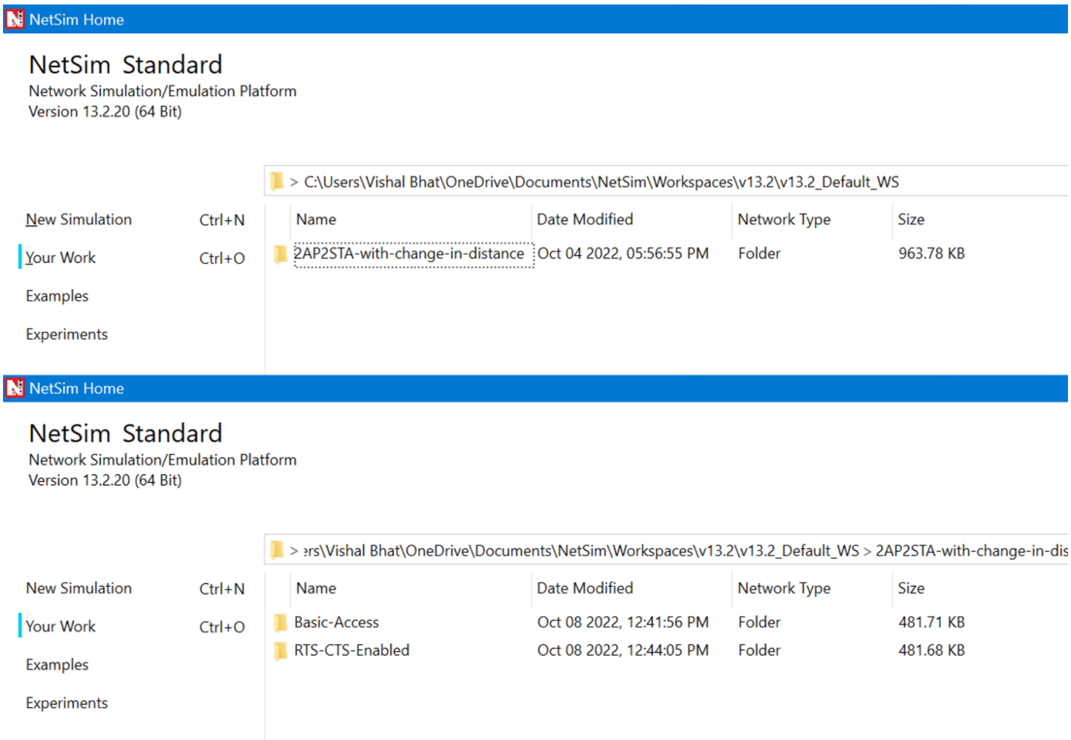
[4] S. Ray, J. Carruthers and D. Starobinski, "RTS/CTS-Induced Congestion in Ad Hoc Wireless LANs," Department of Electrical and Computer Engineering, Boston University.

Appendix 1: Download Link

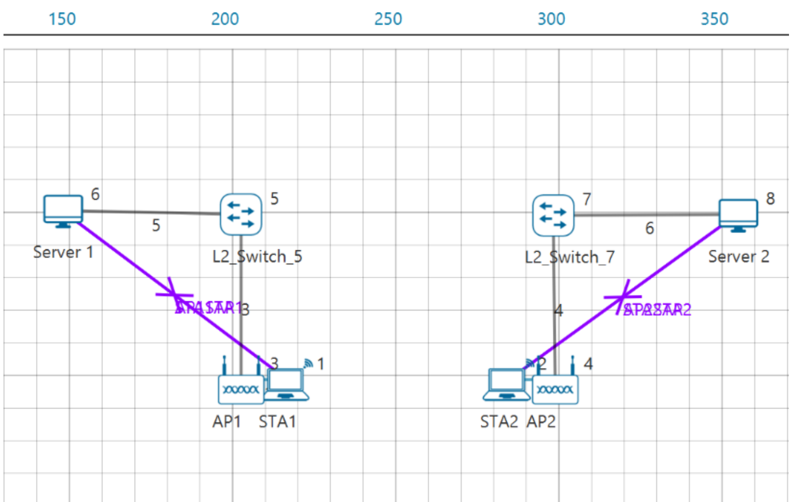
The configuration files (scenario, settings, and other related files) of the examples discussed in this analysis are available for users to import and run in NetSim.

Users can download the files from NetSim's git-repository.
Link: https://github.com/NetSim-TETCOS/2AP2STA-with-change-in-distance_v13.2.20/archive/refs/heads/main.zip

1. Click on the link given and download the folder
2. Extract the zip folder. The extracted project folder consists of one NetSim Experiments file, namely *2AP2STA-with-change-in-distance_v13.2.20.netsimexp*
3. Import per steps given in section 4.9.1 in NetSim User Manual
4. All the experiments can now be seen folder wise within NetSim > Your Work. It will look like the image shown below

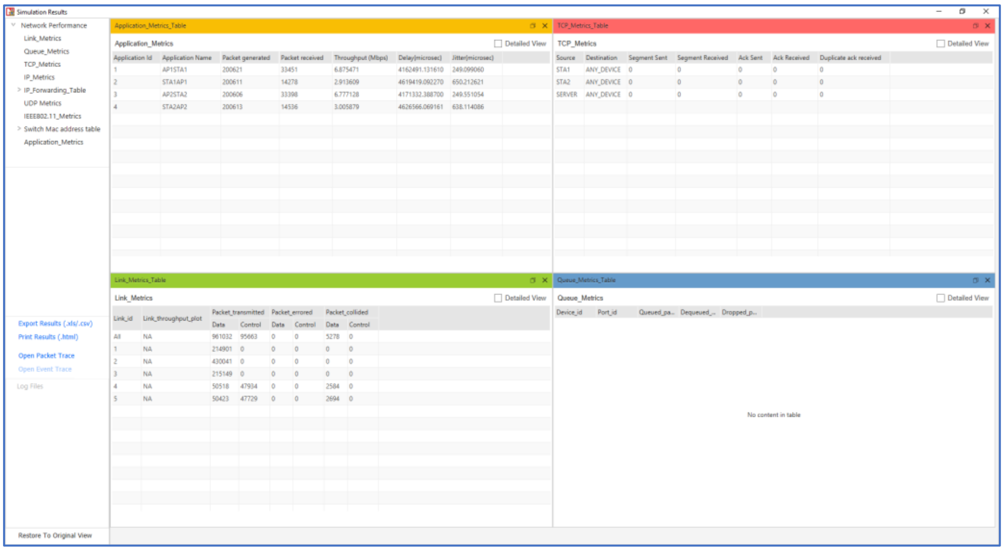


Appendix 2: Network Layout in NetSim



Appendix 3: Calculating packets per second

1. After simulating the scenario, go to NetSim Results Window



2. To calculate the Packet per seconds of AP to STA, calculate the average packet received for AP1STA1 application and AP2STA2 application, and divide the average packets received by simulation time.

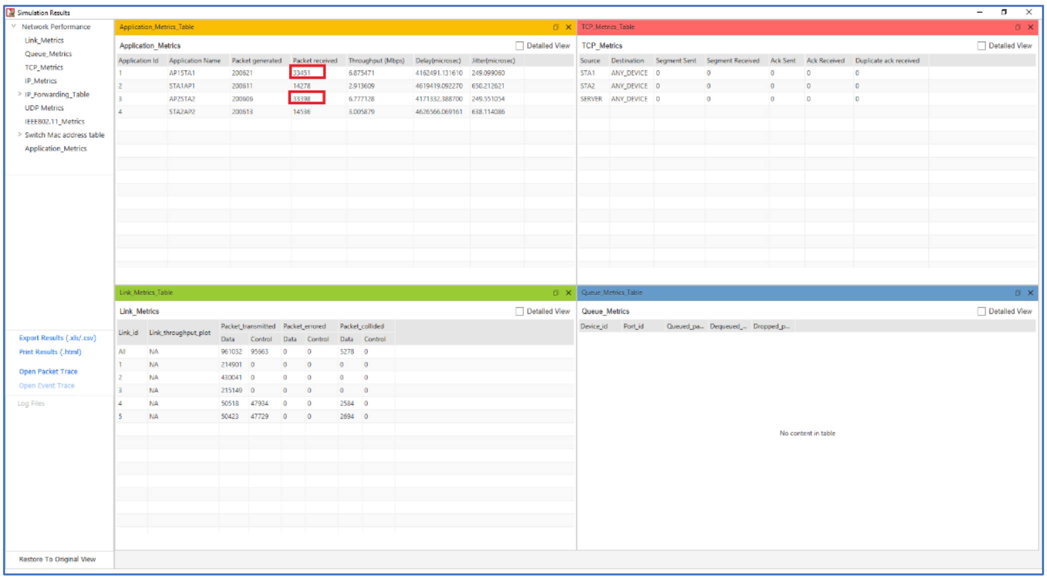
$$Packet\ per\ \sec = \frac{avg(packet\ received)}{simulation\ time}$$

For example;

$$Packets\ received\ for\ application\ AP1STA1 = 33451$$
$$Packets\ received\ for\ application\ AP2STA2 = 33398$$

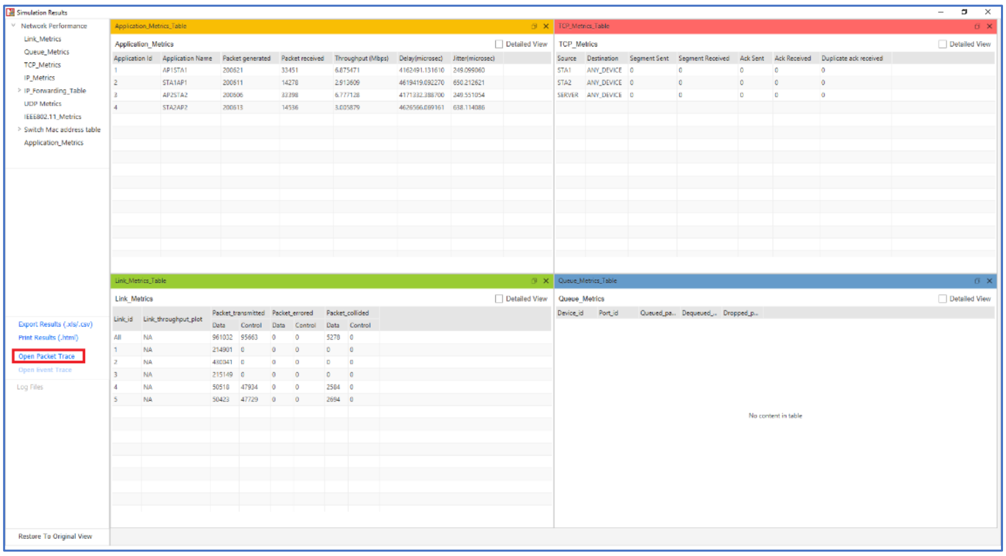
$$Packets\ per\ second\ for\ AP\ STA\ applications = \frac{\frac{33451 + 33398}{2}}{10} = 3342.45$$

Similarly, calculate for STA AP applications also.

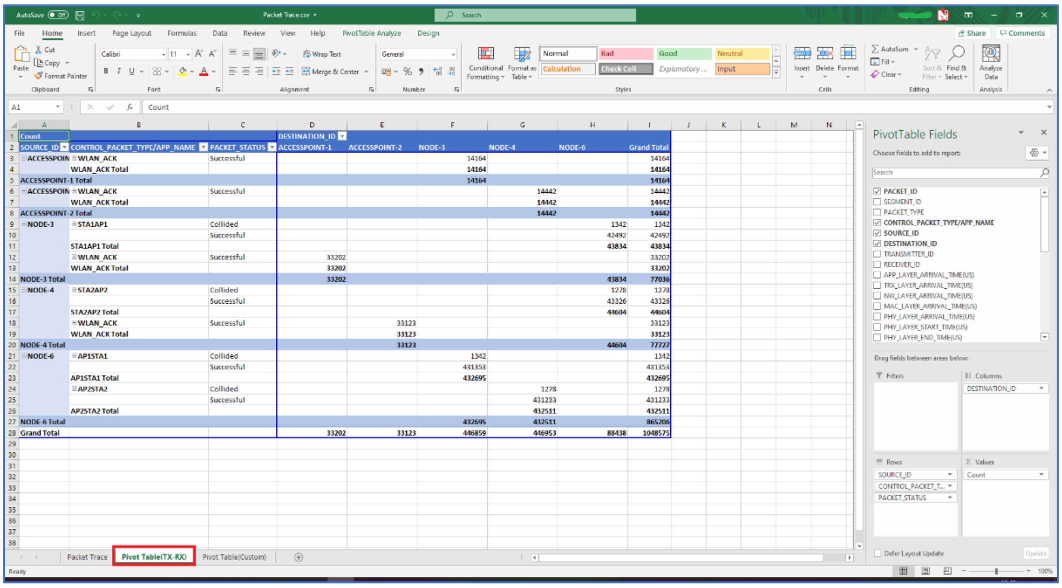


Appendix 4: Computing the packet fail probability

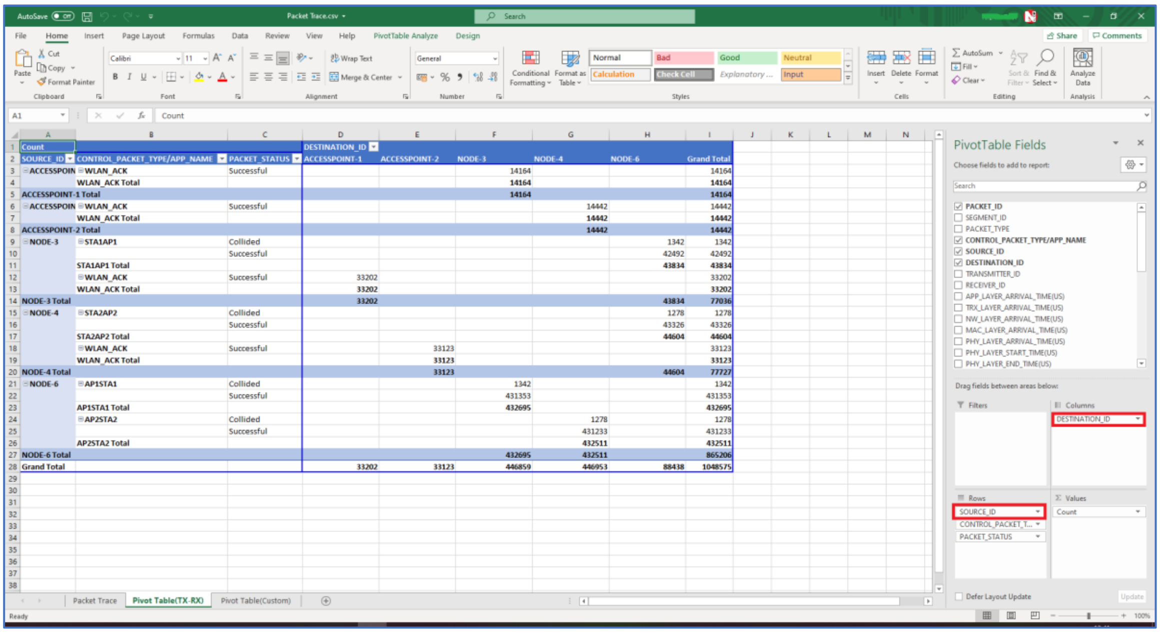
1. After simulation, open the Packet Trace file from NetSim Results window.



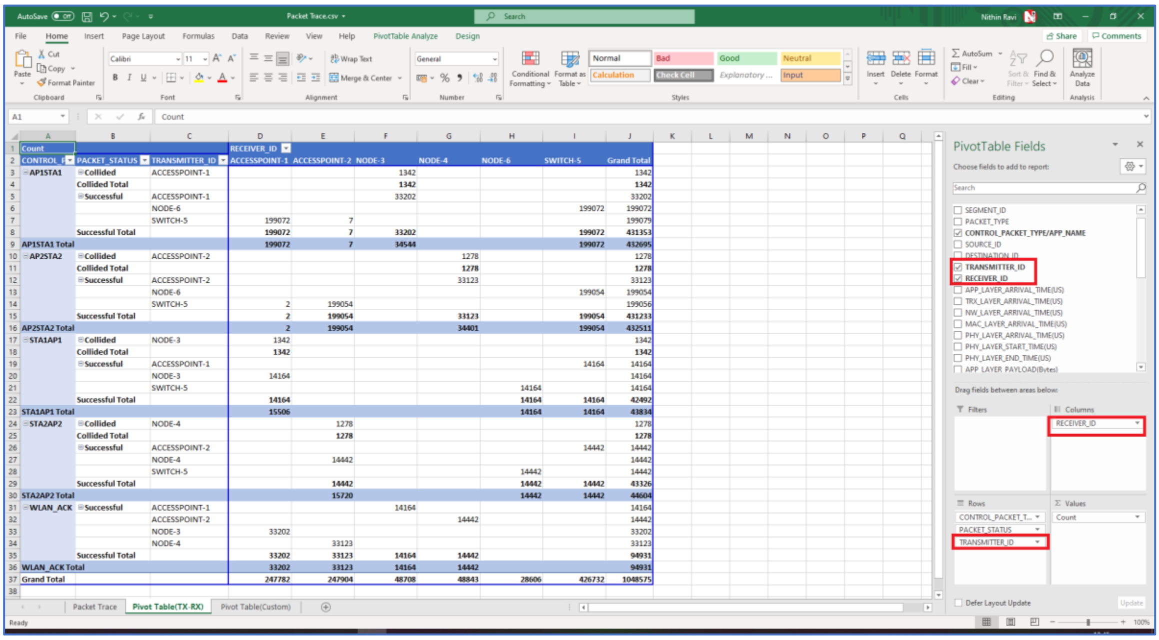
2. Select Pivot Table(Tx-Rx) sheet at the bottom of the sheet. This will load a Pivot Table sheet as shown below:



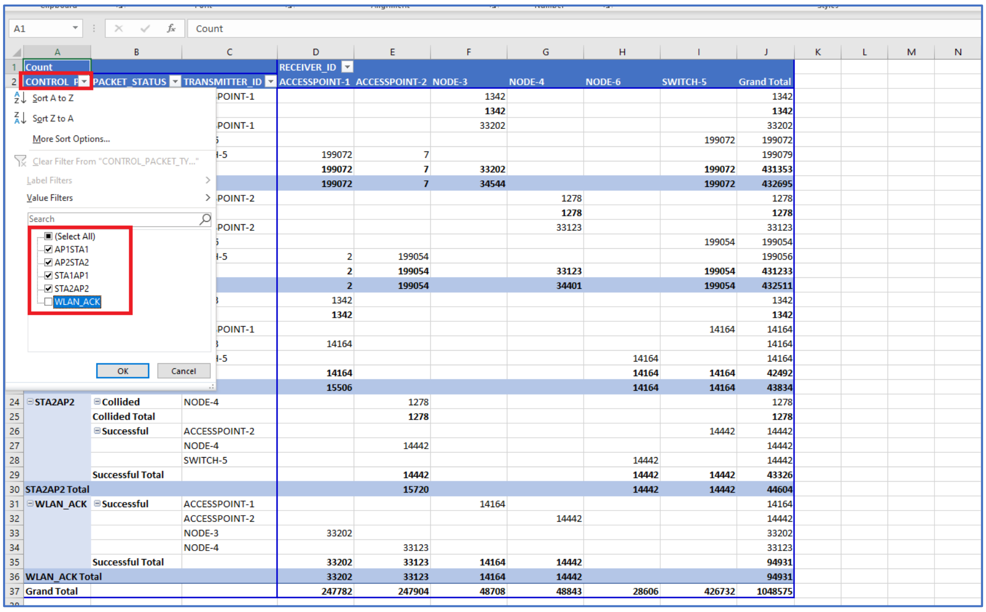
3. Now, remove the SOURCE_ID parameter from Rows field and DESTINATION_ID parameter from Columns field.



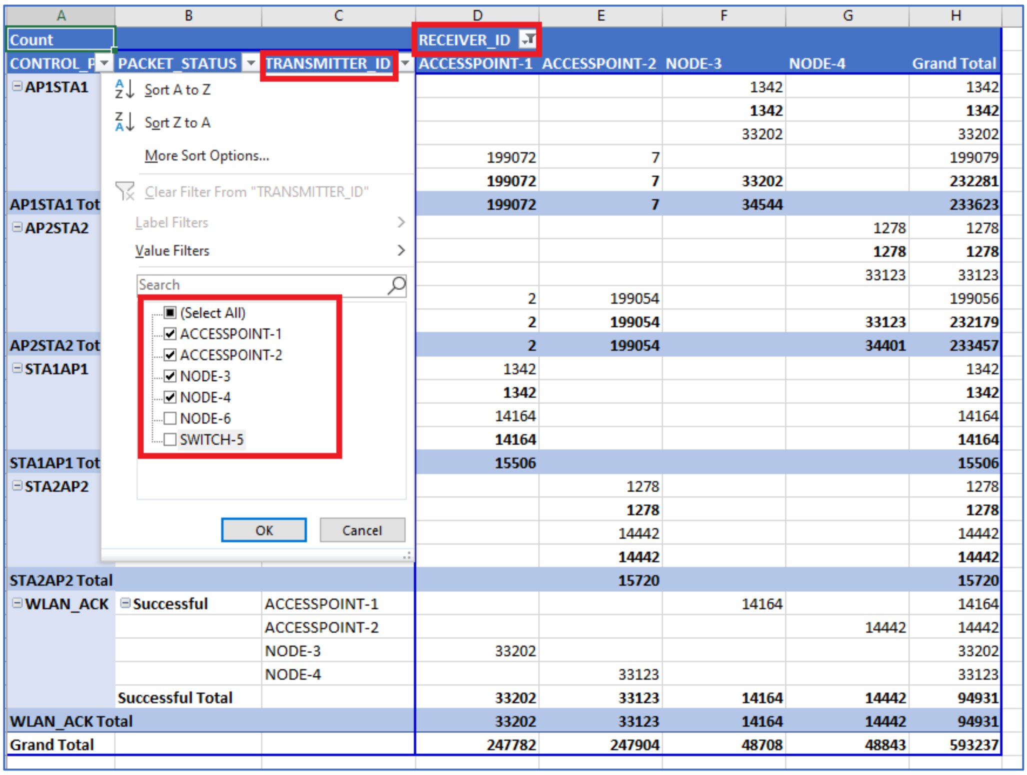
4. Add TRANSMITTER_ID to Rows and RECEIVER_ID to Columns as shown below.



5. Filter Control Packet type to data packets (STA1AP1, STA2AP2 , AP1STA1 and AP2STA2)



6. Filter TRANSMITTER_ID and RECEIVER_ID columns to Access Points and Stations



7. Calculate the collision probability or the packet fail probability using the following equation

$$packet\ fail\ probability = \frac{total\ collided\ packets}{total\ packets}$$

For APSTA transmissions, calculate the packet fail probability for both the applications and take the average of both.
For example;

$$Total\ collided\ packets\ in\ AP1STA1\ application = 1342$$

$$Total\ packets\ transmitted\ in\ AP1STA1\ application = 34544$$

$$Packet\ fail\ probability\ of\ AP1STA1 = \frac{1342}{34544} = 0.0388$$

$$Total\ collided\ packets\ in\ AP2STA2\ application = 1278$$

$$Total\ packets\ transmitted\ in\ AP2STA2\ application = 34401$$

$$Packet\ fail\ probability\ of\ AP2STA2 = \frac{1278}{34401} = 0.0371$$

$$Packet\ fail\ probability\ of\ AP\ STA = avg\ (packet\ fail\ probability\ of\ AP1STA1\ and\ AP2STA2) = \frac{0.0388 + 0.0371}{2} = 0.037$$

Similarly, calculate for STA-AP transmissions.

Count			RECEIVER_ID					
CONTROL_P	PACKET_STATUS	TRANSMITTER_ID	ACCESSPOINT-1	ACCESSPOINT-2	NODE-3	NODE-4	Grand Total	
AP1STA1	Collided	ACCESSPOINT-1			1342		1342	
	Collided Total				1342		1342	0.038849004
	Successful	ACCESSPOINT-1			33202		33202	
	Successful Total				33202		33202	
AP1STA1 Total					34544		34544	
AP2STA2	Collided	ACCESSPOINT-2				1278	1278	
	Collided Total					1278	1278	
	Successful	ACCESSPOINT-2				33123	33123	0.037150083
	Successful Total					33123	33123	
AP2STA2 Total						34401	34401	
STA1AP1	Collided	NODE-3	1342				1342	
	Collided Total		1342				1342	
	Successful	NODE-3	14164				14164	
	Successful Total		14164				14164	0.086547143
STA1AP1 Total			15506				15506	
STA2AP2	Collided	NODE-4		1278			1278	
	Collided Total			1278			1278	
	Successful	NODE-4		14442			14442	
	Successful Total			14442			14442	0.08129771
STA2AP2 Total				15720			15720	
Grand Total			15506	15720	34544	34401	100171	