
ns-3 Wi-Fi 11ax project

Release final

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May 26, 2019

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INTRODUCTION

Overview

The document provides validation and initial testing results of the ns-3 WiFi 802.11ax features, with focus on spatial reuse.

This document is written in Python Sphinx markup and is maintained in the ns-3 folder `src/wifi-he/doc`.

As described in [Sta16], 802.11ax has features to improve overlapping BSS (OBSS) operation in dense environments, including changes to deferral rules and CCA levels. STAs are able to detect whether the received frame is an inter-BSS or an intra-BSS frame by using the new BSS color field carried in the 11ax preamble, and under prescribed conditions, to use a different OBSS PD level that is above the minimum receive sensitivity level, and possibly a reduced transmit power, to send a frame while the channel is occupied by the inter-BSS frame.

This phase of the project is focused towards a basic dense-mode deployment simulation scenario with a number of (overlapping) BSS, each of which can be configured as 802.11ac or 802.11ax BSS. In such a scenario, the hypothesis that 802.11ax can lead to greater system performance can be tested.

The software corresponding to this report resides in a private Bitbucket repository, although portions of the underlying 802.11ax implementation are in the process of being migrated to the mainline ns-3 repository.

Outline

- Section 2 provides an overview of the design of the spatial reuse extensions.
- Section 3 provides instructions on how to run the ns-3 programs.
- Section 4 provides validation results of the underlying ns-3 Wi-Fi models based on TGax calibration scenarios.
- Section 5 provides in-depth results from different parametric studies.
- Section 6 describes open issues and future work.

Spatial Reuse Design

ns-3 support for 802.11ax (High Efficiency (HE) WLAN) ([*Sta16J*]) spatial reuse features are found in the `src/wifi/model` module.

However, scripts to evaluate the performance of these extensions are found in the `src/wifi-he/scripts` directory. These scripts exist in a separate module because we originally thought that 11ax would reside in a separate module from *ns-3*'s `wifi` module, but later we made the decision that 802.11ax extensions should reside in the main `wifi` module.

The implementation includes the following support:

1. A new `HeConfiguration` object to manage 802.11ax-specific configuration, in particular, BSS color parameter.
2. Extensions to the `WifiTxVector` object to carry the BSS color.
3. Extensions to the `WifiPhy` receive methods to model the reception of a notional HE preamble and PHY header, and to convey BSS color and other fields to a separate `ObssPdAlgorithm` object.
4. The `ObssPdAlgorithm` base class allows for different algorithms to be implemented to a common interface. The default algorithm is a `ConstantObssPdAlgorithm`. There exists also an implementation of a `BeaconRssiObssPdAlgorithm` that does not support transmit power control; it is implemented in the `ns3::StaWifiMac` class but will be moved to a subclass of `ObssPdAlgorithm`.

HE PHY preamble and header reception

Once the PHY is done with receiving preambles, headers as well as training fields and is about to start receiving the payload, it checks whether the packet under reception is HE. In this case, it reads the BSS color from the HE SIG field and triggers a trace source named `EndOfHePreamble`. OBSS PD algorithms can connect to this trace source to be notified when reception of a HE packet has started.

OBSS PD Algorithm

`ObssPdAlgorithm` is the base class of OBSS PD algorithms. It implements the common functionalities. First, it makes sure the necessary callbacks are setup. Second, when a PHY reset is requested by the algorithm, it performs the computation to determine the TX power limitation and informs the PHY object.

Constant OBSS PD Algorithm

Constant OBSS PD algorithm is a simple OBSS PD algorithm implemented in the `ConstantObssPdAlgorithm` class.

Once a HE preamble and its header have been received by the PHY, `ConstantObssPdAlgorithm::ReceiveHeSig` is triggered. The algorithm then checks whether this is an OBSS frame by comparing its own BSS color with the BSS color of the received preamble. If this is an OBSS frame, it compare the received RSSI with its configured OBSS PD level value. The PHY then gets reset to IDLE state in case the received RSSI is lower than that constant OBSS PD level value, and is informed about a TX power limitations.

Overview

This section provides an overview of an example script that simulates an 802.11ax spatial reuse scenario, `spatial-reuse.cc`, and describes how parameters can be controlled and changed, and what output is produced.

Additionally, utilities and supporting scripts are also described. These scripts are used to generate experiments that simulate various scenarios and to plot results from those experiments.

Finally, a “HOWTO” guide describes several example bash scripts that can orchestrate various experiments.

`spatial-reuse.cc`

The program `examples/spatial-reuse.cc` allows the user to select various command line parameters that control behaviors of a simulation of a wireless network. Such simulations are especially suited for spatial-reuse evaluations.

Output

By default, the program will simulate 20s of traffic flows for 2 BSSs, each with 1 AP and 1 STA. The APs are separated by 100m, and the STAs are each placed at a random position within a circle of radius 50m centered at the AP. Traffic is allocated at 1 Mbps uplink consisting of 1500 byte packets, and 1 Mbps downlink with 300 byte packets. WiFi standard 802.11ac is used by default with 20 MHz channels and a SISO antenna system, using the constant rate wifi manager for a constant VHT MCS 0. The residential scenario is used, which uses the `Ieee80211IndoorPropagationLossModel`.

```
$ ./waf --run spatial-reuse
```

The above output shows the following results:

```
Uplink interval:+12000000.0ns Downlink interval:+2400000.0ns
ApplicationTxStart: 1 Duration: 20
nBss: 2 nStas/Bss: 1 => nStas: 2
Spatial Reuse Statistics
Scenario: residential
APs: 2
Nodes per AP: 1
Distance between APs [m]: 100
Radius [m]: 50
Uplink [Mbps]: 1
Downlink [Mbps]: 1
Uplink Efficiency 95.64 [%]
```

```
Downlink Efficiency 95.604 [%]
Throughput, AP1 Uplink [Mbps] : 0.9564
Throughput, AP1 Downlink [Mbps] : 0.95604
Throughput, AP2 Uplink [Mbps] : 0.9552
Throughput, AP2 Downlink [Mbps] : 0.95604
Total Throughput Uplink [Mbps] : 1.9116
Total Throughput Downlink [Mbps] : 1.91208
```

These results show that the two networks delivered comparable throughput performance in this scenario.

Additionally, the spatial-reuse script produces a number of output files that are placed in the `scripts/results/` folder. These output files will include the name of the test that is specified with the `-test=<test name>` command line option. The default test name is “test”. Thus, for example, using the default configuration, there will be an output file found as `scripts/results/spatial-reuse-positions-test.csv`.

- `spatial-reuse-positions-<test name>.csv` - The positions of all nodes in the network, used for plotting the topology of the experiment. This file is divided into several sections, with each section separated by two blank lines. The sections of the positions file are: 1) the bounding box of the topology plot, 2) the next `nBss` sections are the locations of the `N` APs of the network, and 3) the remaining `N` sections are the locations of the `n` STAs for each of the `nBss` BSSs.
- `spatial-reuse-<test name>.tr'` - Ascii trace files if `-ascii=1` is specified
- `spatial-reuse-state-<test name>.dat` - PHY states transitions.
- `spatial-reuse-rx-sniff-<test name>.dat` - CSV trace of all received packets, including the receiving node id, the destination node id, the source node id, the receiving node address, the MAC header `addr1` and `addr2` fields, the noise level of the received packet, the RSSI of the received packet, and the packet length of the received packet.
- `spatial-reuse-phy-log-<test name>.dat` - The statistics of all packet arrivals.
- `spatial-reuse-SR-stats-<test name>.dat` - Main spatial reuse statistics output file. This includes 1) a summary of the scenario, 2) the totals of aggregated throughput (uplink and downlink), area capacity, and spectrum efficiency for each AP in the network, and 3) the per-node throughput received by each node in the network.
- `spatial-reuse-A-<test name>.flowmon` - Flowmonitor output file for the UDP flows to and from the primary AP (i.e., for operator “A”) in the network).
- `spatial-reuse-operatorA-<test name>` - Text formatted output of the “per-flow” UDP flows for Operator “A” in the network, including: source address, destination address, total packets sent, and total bytes sent. For received packets, the total received bytes, throughput, total delay, and total jitter values are also provided.

Command Line Options

The complete list of program command lines options and their meanings can be obtained by running the following command:

```
$ ../waf --run "spatial-reuse --PrintHelp"
```

Utilities and Supporting Scripts

spatial-reuse-functions.sh

This is a collection of bash script helper functions that are used by some additional scripts to run experiments. In particular, a bash script function named `run_one()` is defined that runs an ns-3 simulation, and then generates various plots and charts of the results.

The script is invoked by first setting variable values as environment variables. For example, a caller may set a variable as follows:

```
$ export RngRun=7
```

The caller may then invoke the `run_one` function, which uses such parameters to invoke the `spatial-reuse.cc` script. For example, the following shows the first few lines of the `run_one()` function and show the invocation of 3 parameters.

```
#!/bin/bash

# function to run one test
function run_one () {
  echo Running ${test}
  # run the test
  ../../../../waf --run "spatial-reuse \
    --RngRun=${RngRun} \
    --powSta=${powSta} \
    --powAp=${powAp} \
    ...
```

spatial-reuse-positions.plt

This is a gnuplot script that produces a node positions plot. This script has been tested with gnuplot Version 5.0 patchlevel 3. Note that other versions of gnuplot may give different results, or fail to generate plots, due to changing gnuplot parameters and/or features. For example, it is noted that gnuplot linestyles are particularly sensitive to the version of gnuplot used.

ecdf2.py

This is a Python program that post-processes simulation results and produces an Empirical Cumulative Distribution Function (ECDF) plot from a data file. The ECDF is plotted using gnuplot.

Bash scripts

The following bash shell scripts used to execute simulations and validate results.

These scripts are found in the module's `/scripts/` folder.

run-scenarios.sh

This script runs several scenarios defined in [TGax15], including the scenarios for residential, enterprise, small indoor BSSs, and large outdoor BSS.

This script is used to simulate those scenario with results documented in the Results chapter.

run-spatial-reuse-scenarios.sh

This script runs several scenarios that conduct experiments with 2 BSSs and vary parameters, such as the separation distance between the APs and the number of STAs associated with each AP.

This script is used to conduct sensitivity studies of key parameters with results documented in the Results chapter.

run-spatial-reuse-study1.sh

This script runs several scenarios that conduct experiments with 7 BSSs and vary parameters, as defined by parametric study 1 defined in this documentation.

This script assume the use of standard 802.11ac, and serves as a baseline for comparison to 802.11ax results.

run-spatial-reuse-study2.sh

This script runs several scenarios that conduct experiments with 7 BSSs and vary parameters, as defined by parametric study 2 defined in this documentation.

This script assume the use of standard 802.11ax and OBSS_PD enabled.

calibration-scenarios.sh

This script runs several scenarios defined in [TGax15], specifically a subset of the MAC simulator calibration scenarios.

This script is used to simulate those scenarios with results documented in the Results chapter.

calibration-box5.sh

This script runs several scenarios defined in [TGax15], specifically several additional calibration scenarios referred to as the Box5 scenarios in [TGax15].

This script is used to simulate those scenarios with results documented in the Results chapter.

plot-individual.sh

This script generates plots from the results that are generated by the run-spatial-reuse-scenarios.sh script. A set of plots is generated for each scenario that was executed. These plots are used within this documentation.

plot-combined.sh

This script generates additional plots from the results that are generated by the run-spatial-reuse-scenarios.sh script. These plots are specific plots that combine two or more scenarios into a single plot. These plots are used within this documentation.

make-data-files.sh

This script is run after the script run-spatial-reuse-scenarios, and prepares several data files from those results, in preparation for running the plot-individual.sh and plot-combined.sh scripts.

copy-plots-to-doc-figures.sh

This script copies the plots that are referenced in this documentation and that are generated by the `plot.sh` and `plot-combined.sh` scripts. The plots are copied from the location into which they are generated, and into the location where the documentation needs the figures, in order for the documentation generation process to complete.

“How To” Guide to Running Experiments

The following sections describes several example bash scripts that are used to run various experiments. For each experiment set, the bash script name is given along with some remarks that describe what the script does, how it is structured, and what results can be expected.

These scripts can be used as a reference for researchers wishing to create additional experiments.

All scripts can be found in the `wifi-he/scripts/` folder.

These experiments are decomposed into the following subsets:

- Calibration Tests
- TGax Experiments
- Simple Examples
- Bianchi Validation
- Simulation Parameter Sensitivity Study
- Parametric Studies

Calibration Tests

The purpose of the Calibration Tests is to implement the calibration tests outlined in [\[TGax15\]](#) for validation of the Wi-Fi models.

The following bash scripts are available:

- `./calibration-scenarios.sh`
- `./calibration-box5.sh`

The ‘`calibration-scenarios.sh`’ script executes the following calibration tests: 1) Test 1a - MAC overhead w/o RTS/CTS, 2) Test 1b - MAC overhead with RTS/CTS, 3) Test 2a - Deferral Test 1, 4) Test 2b - Deferral Test 2, and 5) Test 3 - NAV Deferral. The tests are launched as separate ns-3 simulations that are run in parallel. Details on these tests can be found in [\[TGax15\]](#). Results of these tests are provided in the Results section of this document. The scripts are provided to allow researchers to recreate the calibration results.

The ‘`calibration-box5.sh`’ script executes the following calibration tests: 1) Box5 - 1BSS DL only, 2) Box5 - 1BSS UL only 1 STA, 3) Box5 - 1BSS UL only 2 STA, 4) Box5 - 1BSS UL only 3 STA, 5) Box5 - 1BSS DL and UL, 6) Box5 - 2BSS Both DL only, 7) Box5 - 2BSS Both UL only, 8) Box5 - 2BSS A DL and B UL, 9) Box5 - 2BSS A UL and B DL.

The tests are launched as separate ns-3 simulations that are run in parallel. Details on these tests can be found in [\[TGax15\]](#). Results of these tests are provided in the Results section of this document. The scripts are provided to allow researchers to recreate the calibration results.

TGax Experiments

The purpose of the TGax Experiments is to implement the TGax scenarios outlined in [TGax15] for validation of the ns-3 simulator.

These scenarios include:

- 1 - Residential Scenario
- 2 - Enterprise Scenario
- 3 - Indoor Small BSSs Scenario
- 4 - Outdoor Large BSS Scenario

These scenarios differ the number and distances of the STAs and APs, and use different propagation loss model parameters.

The following bash script is available:

```
$ ./run-scenarios.sh
```

The tests are launched as separate ns-3 simulations that are run in parallel. Details on these tests can be found in [TGax15]. Results of these tests are provided in the Results section of this document. The scripts are provided to allow researchers to recreate the results for the TGax Experiments.

Simple Examples

The purpose of this simple examples section is to demonstrate some simple usage of the spatial-reuse script and to provide researchers with insights into the network performance of a dense spatial-reuse scenarios sensitive to the variation of key parameters. These tests are based on the Residential Scenario of the TGax Experiments script. A subset of the results of this script is included in the Results section of this document.

Transmitted packets use a payload size of 1500 bytes, with an A-MDPU set to aggregate at most 2 packets (i.e., MaxAmpduSize=3142). Packets are sent at a data rate using MCS=0.

The following bash script is available:

```
$ ./run-spatial-reuse-scenarios.sh
```

The following parameters are varied:

- n - for values 5, 10, and 20 STAs
- d - for values 20, 40, 60, and 80 m
- r - for values 10, 20, and 30 m
- uplink - for values 1, 2, 3, 4, 5, 6 Mbps

The scripts are provided to allow researchers to study the effects on network performance when varying key script parameters.

Bianchi Validation

The purpose of the Bianchi Validation tests is to validate the spatial-reuse script according to the expected performance in light of “Bianchi conditions”, which are generally in the presence of a fully saturated network with each transmitting node having infinite transmission retries, and no hidden nodes.

The scenario places one BSS of interest at the center of the topology, surrounded by 6 other BSSs arranged in a hexagonal pattern. There is 1 AP at the center of each of the 7 total BSSs. The APs are separated by a distance so as to either a) fully decouple the BSSs (i.e., $d=120\text{m}$), or b) fully couple the BSSs (i.e., $d=20\text{m}$). Around each AP there are n STAs that are randomly placed within a circle of radius $r=10\text{m}$ centered at the AP. The number of STAs varies depending on the validation test, but generally varies from 5 to 40 STAs per BSS.

Transmitted packets use a payload size of 1500 bytes, with an A-MDPU set to aggregate at most 2 packets (i.e., $\text{MaxAmpduSize}=3142$). Packets are sent at a data rate using $\text{MCS}=7$. Shadowing loss effects of the propagation loss model are disabled.

A theoretical calculation of the expected throughput is compared to the resulting throughput realized by the ns-3 simulation.

The following bash scripts are available:

```
$ ./bianchi-test1-dl-only.sh
$ ./bianchi-test2-up-only.sh
$ ./bianchi-test3-dl-only.sh
$ ./bianchi-test4-ul-only.sh
```

Test 1 considers the scenario where the BSSs are fully decoupled (with separation distance of 120m between APs) with 40 STAs per BSS receiving downlink traffic only in a fully saturated network.

Test 2 considers the scenario where the BSSs are fully decoupled (with separation distance of 120m between APs) with varying numbers of STAs (e.g., from 5 to 40 in steps of 5) per BSS transmitting uplink traffic only in a fully saturated network.

Test 3 considers the scenario where the BSSs are fully coupled (with separation distance of 20m between APs) with 40 STAs per BSS receiving downlink traffic only in a fully saturated network.

Test 4 considers the scenario where the BSSs are fully coupled (with separation distance of 20m between APs) with varying numbers of STAs (e.g., from 5 to 40 in steps of 5) per BSS transmitting uplink traffic only in a fully saturated network.

The scripts are provided to allow researchers to recreate the validations of the ns-3 simulation performance of dense spatial-reuse scenarios in terms of Bianchi conditions.

Simulation Parameter Sensitivity Study

The purpose of the Simulation Parameter Sensitivity Study is to examine the sensitivity of the `spatial-reuse.cc` script to the following command line option parameters:

```
--applicationStartTx
--duration
--RngRun
```

The script is based on the Bianchi Validation test (Test2) for fully saturated uplink traffic for $n=5$ nodes per BSS, with 1 AP in each of 7 BSSs, where the APs are separated by $d=120\text{m}$.

The following bash script is available:

```
$ ./bianchi-test2-run-sensitivity.sh
```

The tests are launched as separate ns-3 simulations that are run in parallel. The scripts are provided to allow researchers to study the parametric effects of varying parameters that may influence simulation results.

Parametric Studies

The purpose of the Parametric Study 1 is to evaluate spatial reuse effects for dense node scenarios, while varying several parameters, such as:

n - vary the number of STAs associated with each BSS from 5 to 40 (in steps of 5)

offered load - vary the total system offered load (aggregated uplink and downlink) in Mb/s

The scenario places one BSS of interest at the center of the topology, surrounded by 6 other BSSs arranged in a hexagonal pattern. There is 1 AP at the center of each of the 7 total BSSs. The APs are separated by a distance of $d=34.64\text{m}$, as modeled in the Residential Scenario described in [TGax15]. Around each AP there are n STAs that are randomly placed within a circle of radius $r=10\text{m}$ centered at the AP. The number of STAs varies from 5 to 40 STAs per BSS.

Transmitted packets use a payload size of 1500 bytes, with a `MaxAmpduSize=65535`. Packets are sent using the ns-3 Wifi IdealRateManager, which adapts the transmission rate per node based on the received SNR.

The following bash script is available:

```
$ ./run-spatial-reuse-study1.sh
```

Running this script produces another script, 'study1.sh' that must then be run.

The tests are launched as separate ns-3 simulations that are run in parallel. The scripts are provided to allow researchers to study the effects of varying key parameters in a baseline 802.11ac network. A subset of these results are provided in the Results section of this document.

It is expected that throughput increases as offered load increases, but plateaus. Throughput also decreases as the number of nodes per BSS is increased.

This study serves as a baseline evaluation of dense spatial-reuse scenario where all nodes are configured to operate according to the 802.11ac standard. The script serves as a starting point for researchers that wish to evaluate the comparable performance found by varying other key parameters.

For 802.11ax and OBSS_PD enabled tests, the following bash script is available:

```
$ ./run-spatial-reuse-study2.sh
```

Running this script produces another script, 'study2.sh' that must then be run.

VALIDATION

Overview

In this section we first describe the calibration process followed to achieve comparable results from the WiFi module. Then we describes the test suites that are provided in order to validate the proper functionality and correct simulation output of the module.

Calibration Process

To validate the 11ax model implementations, several experiments were conducted using ns-3 scripts to repeat the calibration tests and scenarios outlines in [TGax15]. The parameters as noted in [TGax15] are used to set up ns-3 simulations, and any deviations from these parameters are noted below.

The document [TGax15] defines simulation scenarios to be used for

- Evaluation of performance of proposed 11ax features
- Generation of results for simulators calibration purposes

These two concepts are generally divided into two sets of simulation scenarios that we refer to as: 1) Calibration Tests and 2) TGax Scenarios.

The Calibration Tests are used to confirm the calibration of the ns-3 simulator to expected results. The TGax scenarios evaluate the expected performance of the 11ax features, via ns-3 simulations.

Calibration Tests

The calibration tests are described in [TGax15] in the section titled “Scenarios for calibration of MAC simulator”.

The following tests are the subset of the TGax calibration tests that have been simulated in ns-3:

- Test 1a - MAC overhead w/o RTS/CTS
- Test 1b - MAC overhead w/ RTS/CTS
- Test 2a - Deferral Test 1
- Test 2b - Deferral Test 2
- Test 3 - NAV Deferral

Generally, these tests are quite simple and limit the traffic flow. For example, the topology of Test 1a and Test 1b is a single AP with a single STA with uplink traffic only from the STA to the AP. The goal of this test is verify that the simulator can correctly handle the basic frame exchange procedure.

Test 2a and Test 2b extend the topology to 2 APs each with 1 STA and test that the simulator correctly handles the deferral procedure after collisions happen without hidden nodes.

Test 3 is the same as Test 2b, but with RTS/CTS on.

All tests assume that all packets offered to the MAC at the sender are successfully received at the receiver (i.e., PER is 0).

All nodes are configured to use the 11ax features in the 5GHz band with a 20 MHz bandwidth per channel. The power at the AP (20 dBm) is slightly higher than the power at the STAs (15 dBm).

Senders transmit packets of 1500 bytes using MPDU aggregation with a 2 MPDUs per A-MPDU limit. Data rates using MCS 0 are assumed.

Path loss uses the 'residential' scenario described later.

Common Parameters

The following parameters are set for all all calibration scenarios.

- `RngRun = 1`
- `powSta = 15`
- `powAp = 20`
- `duration = 10.0`
- `enableRts = 0`
- `standard = 11ax_5GHZ`
- `bw = 20`
- `MCS = 0`
- `payloadSize = 1500`
- `txStartOffset = 5`
- `enableObssPd = 1`
- `txGain = 0`
- `rxGain = 0`
- `antennas = 1`
- `maxSupportedTxSpatialStreams = 1`
- `maxSupportedRxSpatialStreams = 1`
- `performTgaxTimings = 1`
- `scenario = residential`
- `nBss = 2`
- `maxAmpduSize = 3140`
- `nodePositionsFile = NONE`
- `enablePcap = 0`
- `enableAscii = 0`
- `obssPdThreshold = -82`

- `useIdealWifiManager = 0`

Test 1a - MAC overhead w/o RTS/CTS

The goal of this test is to verify whether the simulator can correctly handle the basic frame exchange procedure, including AIFS+backoff procedure and A-MPDU + SIFS + BA sequence, and also to make sure the overheads are computed correctly.

The simulation parameters vary from the common parameters by reducing the number of BSSs to $n_{BSS}=1$, and the number of STAs also to $n=1$, where the single STA is dropped into a random position with a radius of $r=30m$ centered at the AP. An total offered load of 10 Mbps is allocated to uplink traffic only.

The following parameters further refine the Test 1a calibration scenario from the common parameters.

- `test = calibration-test1a`
- `d = 1000`
- `r = 30`
- `nBss = 1`
- `n = 1`
- `uplink = 10.0`
- `downlink = 0.0`
- `txRange = 54`

Results

The figures in the section were generated using the ns-3-dev-11ax repository as of commit changeset c85f4dc.

The node positions for the calibration test1a scenario are given below.

Figure *Node positions for the calibration test 1a*. illustrates the node positions of the calibration test 1a scenario.

We can see that there is one BSS with one AP at its center, and 1 STA at a random position within the $r=30m$ radius about the AP.

The simulation results in throughput at the AP of 6.627 Mbps, or 66.27% of the 10 Mbps offered load, indicating that this simulation scenario saturates the network.

Since there is only 1 transiting STA, all signal levels and noise levels from the perspective of the receiving AP should be identical, as the STA is not moving, and there are no other signals in the network that interfere with its transmissions. The Empirical Cumulative Distribution Function (ECDF) for the signal level and noise levels are provided below, and show that there is no variation among the levels.

The ECDF of the signals received by AP1 is given below.

Figure *ECDF of the signals received by AP1 for the calibration test 1a*. illustrates the ECDF of the signals received by AP1 for the calibration test 1a scenario.

The ECDF of the noise levels received by AP1 is given below.

Figure *ECDF of the noise level received by AP1 for the calibration test 1a*. illustrates the ECDF of the noise levels received by AP1 for the calibration test 1a scenario.

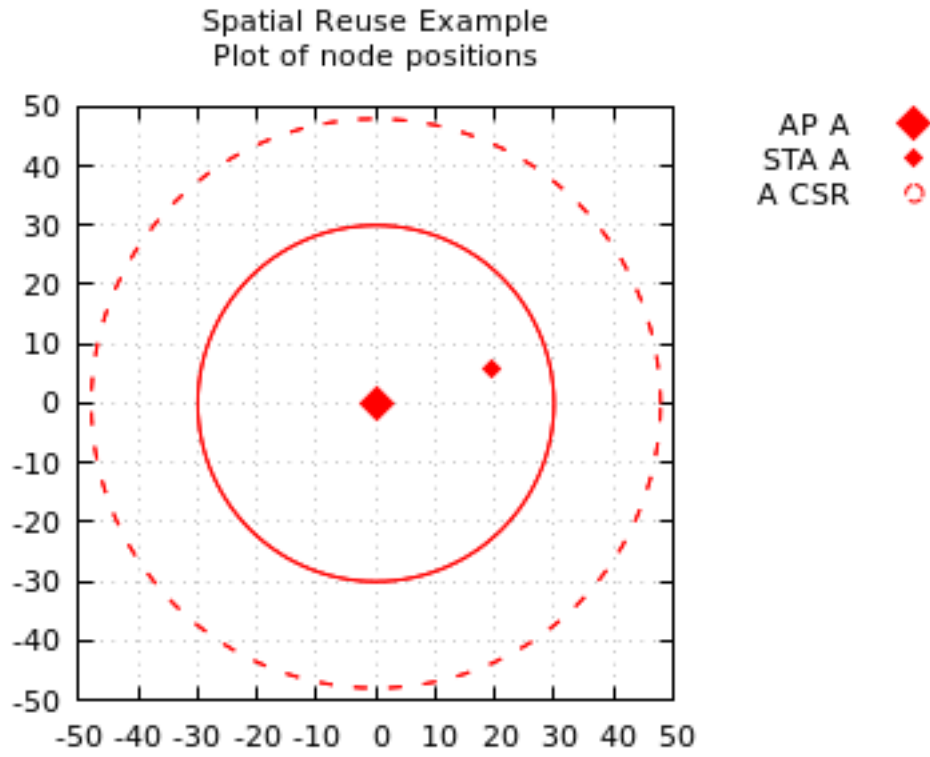


Fig. 4.1: Node positions for the calibration test 1a.

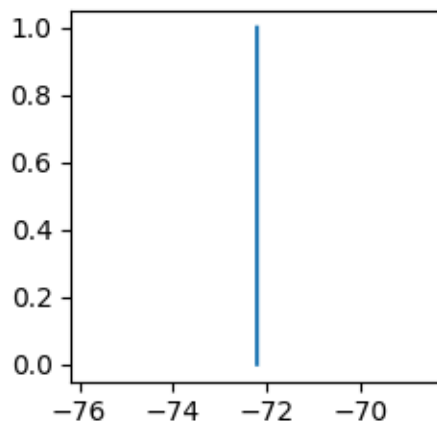


Fig. 4.2: ECDF of the signals received by AP1 for the calibration test 1a.

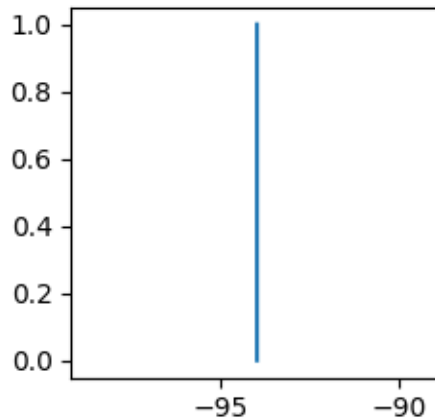


Fig. 4.3: ECDF of the noise level received by AP1 for the calibration test 1a.

Test 1b - MAC overhead w/ RTS/CTS

Test 1b is nearly identical to Test 1a, except that RTS/CTS is enabled in Test 1b, whereas it is disabled in Test 1a. Thus, this test case is designed to further verify whether the simulator correctly handles the frame exchange procedure with RTS/CTS protection based on test1a. It also tests whether the correct overhead computation with RTS /CTS.

The following parameters further refine the Test 1b calibration scenario from the common parameters.

- `test = calibration-test1b`
- `d = 1000`
- `r = 30`
- `nBss = 1`
- `n = 1`
- `uplink = 10.0`
- `downlink = 0.0`
- `enableRts = 1`
- `txRange = 54`

Results

The node positions for the calibration test1b scenario are identical to test1a.

The simulation results in throughput at the AP of 6.4452 Mbps, or 64.45% of the 10 Mbps offered load, indicating that this simulation scenario saturates the network. With CTS/RTS enabled, the effective throughput is lower for Test 1b than it is with Test 1a, where CTS/RTS is disabled.

Since there is only 1 transiting STA, all signal levels and noise levels from the perspective of the receiving AP should be identical, as the STA is not moving, and there are no other signals in the network that interfere with its transmissions. The Empirical Cumulative Distribution Function (ECDF) for the signal level and noise levels are provided below, and show that there is no variation among the levels.

Test 2a - Deferral Test 1

The goal of this test is to verify whether the simulator can correctly handle the deferral procedure after collision happens without hidden nodes. It also checks whether deferral because of energy levels is happening correctly.

The topology of this test assumes two APs each with one STA, such that each STA is essentially co-located with the other AP. For example, AP1 and STA2 are essentially co-located. Each STA generated uplink traffic to its AP. Because of the co-location of nodes, we can expect transmission collisions that require the deferral procedure.

The following parameters further refine the Test 2a calibration scenario from the common parameters.

- `test = calibration-test2a`
- `d = 10`
- `r = 10`
- `nBss = 2`
- `n = 1`
- `uplink = 10.0`
- `downlink = 0.0`
- `enableRts = 0`
- `txRange = 54`

Results

The node positions for the calibration test2a scenario are given below.

Figure *Node positions for the calibration test 2a*. illustrates the node positions of the calibration test 2a scenario.

We can see that there are two BSS each with one AP at its center that are separated by $d=10\text{m}$. There is 1 STA for each BSS placed in a random position within the $r=10\text{m}$ radius about the corresponding AP.

Because all of the nodes are within the Carrier Sense Range (CSR) of the each AP, we can expect transmission collisions to require the deferral procedure.

The simulation results in throughput of 3.042 Mbps and 3.0528 Mbps at AP1 and AP2, respectively. This is 30.04% and 30.05%, respectively, of the 10 Mbps offered load. The results indicate that this simulation scenario saturates the network and results in significantly lower throughput as compared to the Test 1a, where only 1 STA was transmitting without any potential transmission interference from other nodes. The reduced throughput is explained by the deferral procedure.

The signal levels at each receiving AP for the transmissions of its associated STA should be identical, as the STA is not moving. The Empirical Cumulative Distribution Function (ECDF) for the signal level and noise levels are provided below, and show that there is no variation among the levels within each respective BSS.

The ECDF of the signals received by AP1 and AP2 are given below.

Figure *ECDF of the signals received by AP1 for the calibration test 2a*. illustrates the ECDF of the signals received by AP1 for the calibration test 2a scenario.

Figure *ECDF of the signals received by AP2 for the calibration test 2a*. illustrates the ECDF of the signals received by AP2 for the calibration test 2a scenario.

The ECDF of the noise levels received by AP1 and AP2 are given below.

Figure *ECDF of the noise level received by AP1 for the calibration test 2a*. illustrates the ECDF of the noise levels received by AP1 for the calibration test 2a scenario.

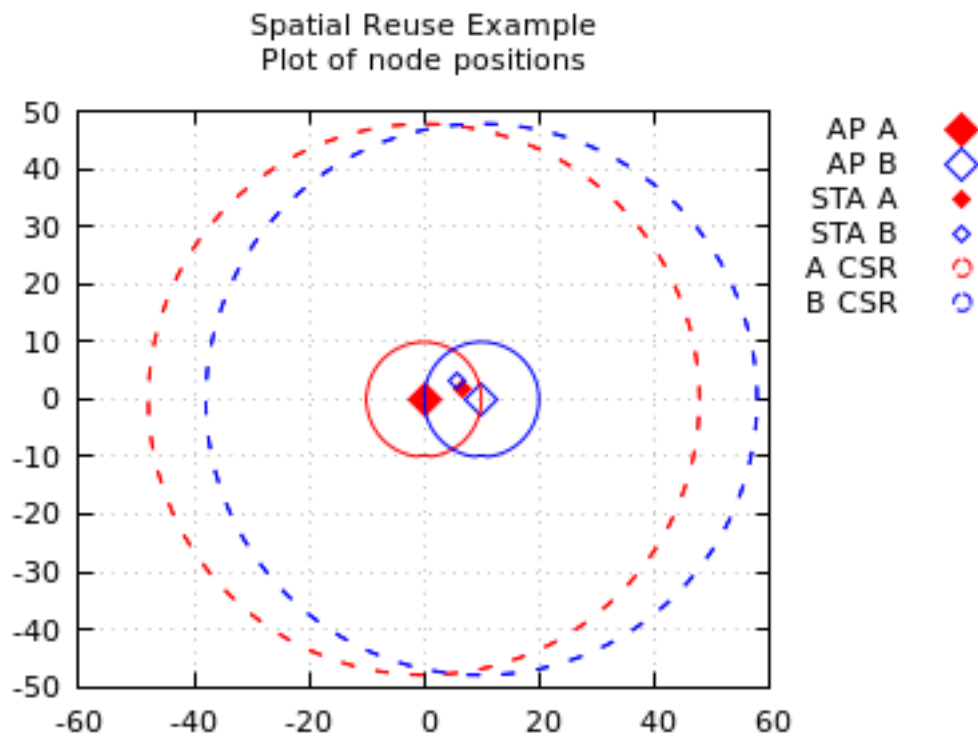


Fig. 4.4: Node positions for the calibration test 2a.

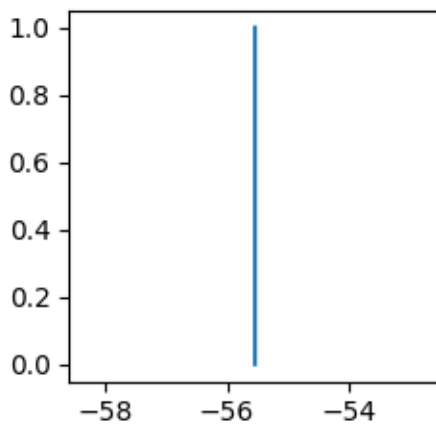


Fig. 4.5: ECDF of the signals received by AP1 for the calibration test 2a.

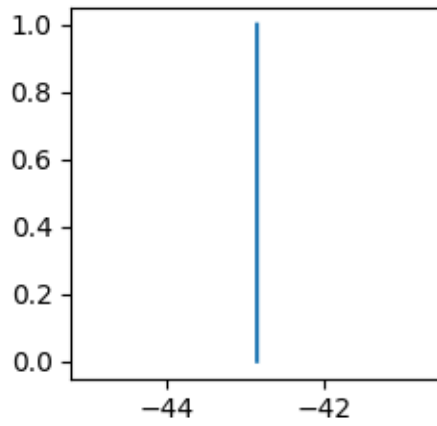


Fig. 4.6: ECDF of the signals received by AP2 for the calibration test 2a.

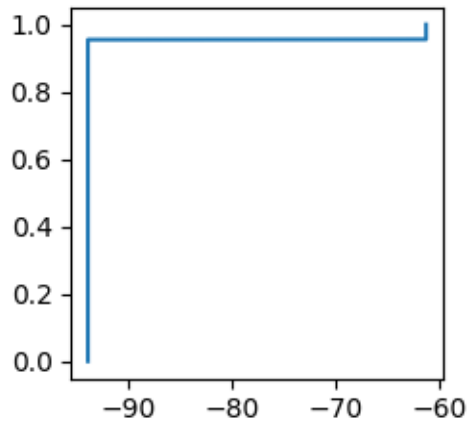


Fig. 4.7: ECDF of the noise level received by AP1 for the calibration test 2a.

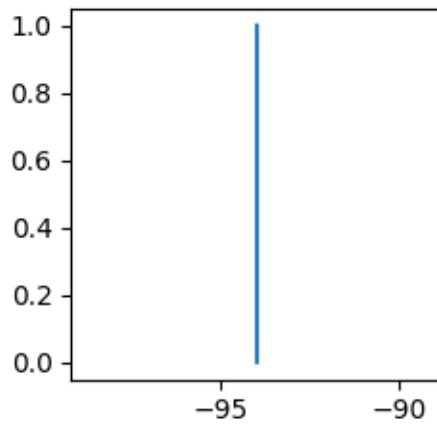


Fig. 4.8: ECDF of the noise level received by AP2 for the calibration test 2a.

Figure *ECDF of the noise level received by AP2 for the calibration test 2a*. illustrates the ECDF of the noise levels received by AP2 for the calibration test 2a scenario.

Test 2b - Deferral Test 2

The goal of this test case is to verify that the simulator correctly handles the deferral procedure after collisions happens with the existence of hidden nodes.

The topology of this test is similar to that of Test 2a, except that the APs are further separated so that they cannot hear each other, while the STAs are essentially co-located.

The following parameters further refine the Test 2a calibration scenario from the common parameters.

- `test = calibration-test2b`
- `d = 20`
- `r = 10`
- `nBss = 2`
- `n = 1`
- `uplink = 10.0`
- `downlink = 0.0`
- `enableRts = 0`
- `txRange = 54`

Results

The node positions for the calibration test2b scenario are given below.

Figure *Node positions for the calibration test 2b*. illustrates the node positions of the calibration test 2b scenario.

We can see that there are two BSS each with one AP at its center that are separated by $d=20\text{m}$. There is 1 STA for each BSS placed in a random position within the $r=10\text{m}$ radius about the corresponding AP. The two STAs are near one another.

The simulation results in throughput of 3.4416 Mbps and 3.3492 Mbps at AP1 and AP2, respectively. This is 34.16% and 33.49%, respectively, of the 10 Mbps offered load. The results indicate that this simulation scenario saturates the network and results in significantly lower throughput as compared to the Test 1a, where only 1 STA was transmitting without any potential transmission interference from other nodes. The reduced throughput is explained by the deferral procedure.

The signal levels at each receiving AP for the transmissions of its associated STA should be identical, as the STA is not moving. The Empirical Cumulative Distribution Function (ECDF) for the signal level and noise levels are provided below, and show that there is no variation among the levels within each respective BSS.

The ECDF of the signals received by AP1 and AP2 are given below.

Figure *ECDF of the signals received by AP1 for the calibration test 2b*. illustrates the ECDF of the signals received by AP1 for the calibration test 2b scenario.

Figure *ECDF of the signals received by AP2 for the calibration test 2b*. illustrates the ECDF of the signals received by AP2 for the calibration test 2b scenario.

The ECDF of the noise levels received by AP1 and AP2 are given below.

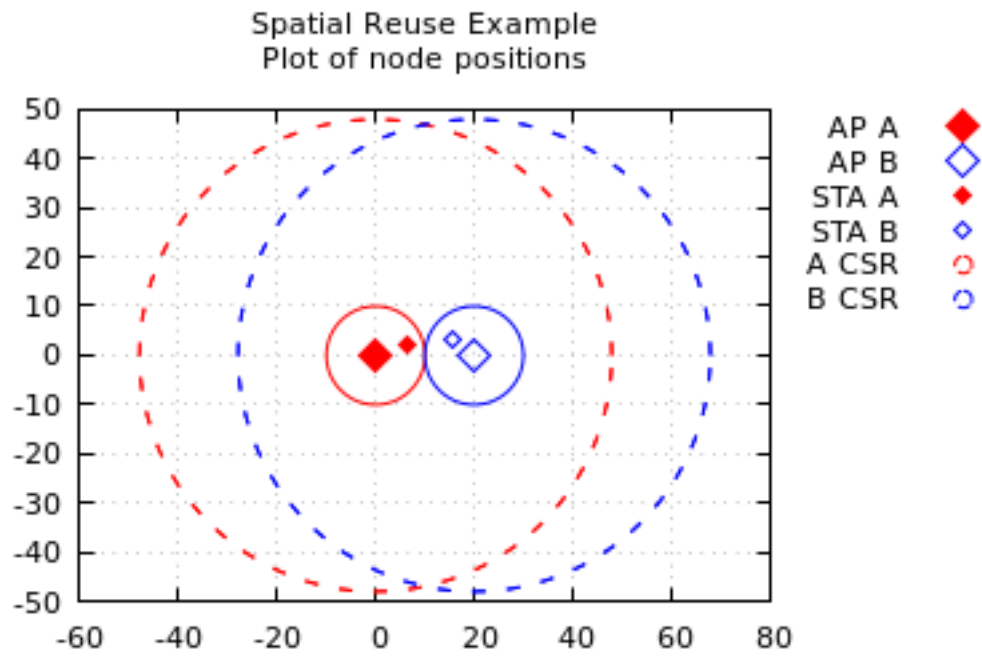


Fig. 4.9: Node positions for the calibration test 2b.

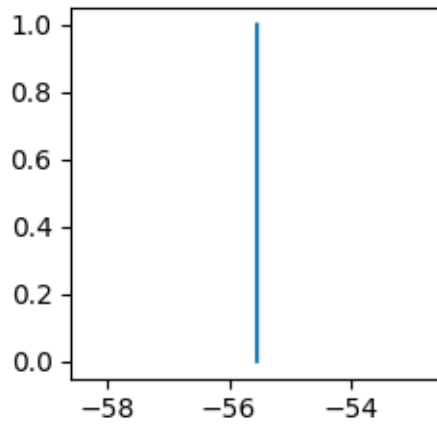


Fig. 4.10: ECDF of the signals received by AP1 for the calibration test 2b.

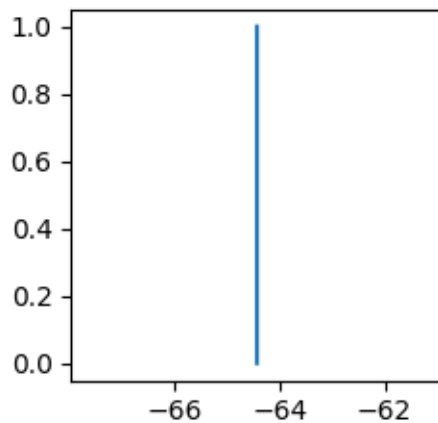


Fig. 4.11: ECDF of the signals received by AP2 for the calibration test 2b.

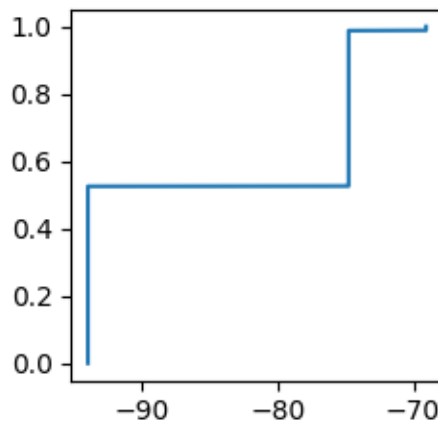


Fig. 4.12: ECDF of the noise level received by AP1 for the calibration test 2b.

Figure *ECDF of the noise level received by AP1 for the calibration test 2b*. illustrates the ECDF of the noise levels received by AP1 for the calibration test 2b scenario.

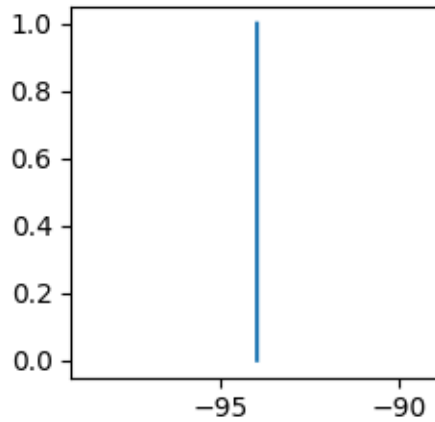


Fig. 4.13: ECDF of the noise level received by AP2 for the calibration test 2b.

Figure *ECDF of the noise level received by AP2 for the calibration test 2b*. illustrates the ECDF of the noise levels received by AP2 for the calibration test 2b scenario.

Test 3 - NAV Deferral

NOTE: Currently Test 3 fails to complete, and documentation results are therefore incomplete.

This test is the same as test 2b, but with RTS/CTS on.

The topology of this test is identical to that of Test 2b.

The following parameters further refine the Test 3 calibration scenario from the common parameters.

- `test = calibration-test3`
- `d = 20`
- `r = 10`
- `nBss = 2`
- `n = 1`
- `uplink = 10.0`
- `downlink = 0.0`
- `enableRts = 1`
- `txRange = 54`

Results

The simulation results in throughput of 3.2664 Mbps and 3.2076 Mbps at AP1 and AP2, respectively. This is 32.66% and 32.08%, respectively, of the 10 Mbps offered load. The results indicate that this simulation scenario saturates the network and results in significantly lower throughput as compared to the Test 1a, where only 1 STA was transmitting

without any potential transmission interference from other nodes. The reduced throughput is explained by the deferral procedure.

Box5 Calibration Tests

In addition to the calibration tests mentioned above, additional tests are defined in [TGax15] for “Box5 calibration”. These tests assume specific node locations for 3 BSSs and the STAs associated with them.

The box5 calibration tests are described in [TGax15] in the section titled “Scenarios for calibration of Box5 simulator”.

The following TGax Box5 calibration tests that have been simulated in ns-3:

- Test 1 - 1 BSS, Downlink only
- Test 2 - 1 BSS, Uplink only, 1 STA
- Test 3 - 1 BSS, Uplink only, 2 STAs
- Test 4 - 1 BSS, Uplink only, 3 STAs
- Test 5 - 1 BSS, Downlink and Uplink
- Test 6 - 2 BSS, both Downlink only
- Test 7 - 2 BSS, both Uplink only
- Test 8 - 2 BSS, A Downlink and B Uplink
- Test 9 - 2 BSS, A Uplink and B Downlink

Generally, these tests are similar to the calibration scenarios described above, except that these box5 scenarios have precise locations for all nodes. This feature is modelled in ns-3 using the MobilityHelper and a positions trace file was created to represent the node locations.

Path loss uses the ‘residential’ scenario described later.

Common Parameters

The following parameters are set for all all calibration scenarios.

- `RngRun = 1`
- `powSta = 15`
- `powAp = 20`
- `duration = 3.0`
- `enableRts = 0`
- `standard = 11ax_5GHZ`
- `bw = 80`
- `MCS = 5`
- `payloadSize = 1500`
- `txStartOffset = 5`
- `enableObssPd = 1`
- `txGain = 0`

- `rxGain = 0`
- `antennas = 1`
- `maxSupportedTxSpatialStreams = 1`
- `maxSupportedRxSpatialStreams = 1`
- `performTgaxTimings = 1`
- `scenario = indoor`
- `nBss = 1`
- `maxAmpduSize = 65535`
- `nodePositionsFile = src/wifi-he/scripts/box5.ns2`
- `enablePcap = 0`
- `enableAscii = 0`
- `obssPdThreshold = -82`
- `useIdealWifiManager = 0`

Validation

The figures in the section were generated using the ns-3-dev-11ax repository as of commit changeset c85f4dc.

The validation tests describe here follow the tests described in [\[TGax15\]](#) in the section titled “Scenarios summary”.

These scenarios are more extensive than the calibration scenarios documented above.

The following tests are the subset of the TGax scenarios that have been simulated in ns-3:

- Test 1 - Residential Scenario
- Test 2 - Enterprise Scenario
- Test 3 - Indoor Small BSSs Scenario
- Test 4 - Outdoor Large BSS Scenario

Generally, these tests introduce more densely arranged scenarios with larger numbers of STAs and APs that are near one another. Such scenarios are useful in evaluating the spatial reuse features of the 802.11ax standard. The scenarios differ in the distances between APs, the number of STAs per BSS, and the path loss models used.

Common Parameters

All tests assume that all packets offered to the MAC at the sender are successfully received at the receiver (i.e., PER is 0).

All nodes are configured to use the 11ax features in the 5GHz band with a 80 MHz bandwidth per channel. The power at the AP (20 dBm) is slightly higher than the power at the STAs (15 dBm).

Senders transmit packets of 1500 bytes using MPDU aggregation with a 2 MPDUs per A-MPDU limit. Data rates using MCS 0 are assumed.

Path loss is distance-based and are evaluated with the operating carrier frequency (i.e., 5 GHz).

Nodes are placed assuming 2-D positions, and antenna heights are thus assumed to be 0m.

The following parameters are set for all all validation scenarios.

- RngRun = 1
- powSta = 15
- powAp = 20
- duration = 10.0
- enableRts = 0
- standard = 11ax_5GHZ
- bw = 80
- MCS = 0
- payloadSize = 1500
- txStartOffset = 5
- enableObssPd = 1
- txGain = 0
- rxGain = 0
- antennas = 1
- maxSupportedTxSpatialStreams = 1
- maxSupportedRxSpatialStreams = 1
- performTgaxTimings = 1
- scenario = residential
- nBss = 2
- maxAmpduSize = 3140
- nodePositionsFile = NONE
- enablePcap = 0
- enableAscii = 0
- obssPdThreshold = -82
- useIdealWifiManager = 0

It is noted that some parameters vary from those mentioned in [TGax15]. In particular, the ns-3 simulations assume 1 antenna per node (AP or STA) with no antenna gains. Contrastingly, the parameters given in [TGax15] assume 4 antennas per AP with 0 dBi gain, and 2 antennas per STA with -2 dBi gain.

Test 1 - Residential Scenario

The residential scenario is derived from an environment described by a multi-floor building, where there are 2 - 10m x 10m apartments on each floor. One AP and some number of STAs are assumed in each apartment.

The scenario is simulated in ns-3 as follows: 2 APs are placed $d=10\text{m}$ apart, each with $n=10$ STAs that are dropped within a circle of $r=5\text{m}$ around the AP.

Traffic flow is modelled as a total aggregated offered load of 10 Mbps of uplink traffic only. With a total uplink load of 10 Mbps and $n=10$ STAs per network, the uplink load per STA is $10\text{ Mbps} / 10\text{ nodes} = 1\text{ Mbps}$ per STA. Note that this load is a deviation from the scenario as documented in [TGax15], in which different traffic models are assigned separately to each “apartment”.

The residential path loss model is given by:

Pathloss model

$$PL(d) = 40.05 + 20 * \log_{10}(fc/2.4) + 20 * \log_{10}(\min(d,5)) + (d > 5) * 35 * \log_{10}(d/5) + 18.3 * F^{(F+2)/(F+1)-0.46} + 5 * W$$

where:

- d = max(3D distance [m], 1)
- fc = frequency [GHz]
- F = number of floors traversed
- W = number of walls traversed in x-direction plus number of walls traversed in y-direction

This pathloss model is modelled in ns-3 using the Ieee80211axIndoorPropagationLoss model with attribute values “DistanceBreakPoint” = 5, “Walls” = 1, and “WallsFactor” = 5.

The following parameters further refine the Residential Scenario from the common parameters.

- test = TGax-test1
- d = 10
- r = 5
- n = 10
- uplink = 10.0
- downlink = 0.0
- txRange = 54
- scenario = residential

Results

The node positions for the Residential Scenario are given below.

Figure *Node positions for the Residential Scenario*. illustrates the node positions of the Residential Scenario.

We can see that there are two BSS each with one AP at its center, representing two apartments, each with 10 STAs at random position within the r=5m radius about the AP.

The simulation results in throughput of 8.3652 Mbps and 8.3736 Mbps at AP1 and AP2, respectively. This is 83.65% and 83.74%, respectively, of the 10 Mbps offered load. The results indicate that this simulation scenario saturates the network.

Since each network has a number of sending STAs, an examination of the distribution of signal level and noise levels, from the perspective of the receiving AP, helps provide insight into the behavior of the network on a node-by-node level. The Empirical Cumulative Distribution Function (ECDF) for the signal level and noise levels are provided below, and show that there is variation among the levels.

Steps in the signal and noise level plots indicate transitions in the data that generally correspond to different nodes. For example, the plots below are generated from the scenario with n=10 STAs associated per AP, and there are roughly 10 steps. Vertical lines indicate that the signal and noise levels per STA remain constant, which is explained by the deterministic evaluation of the signal at the receiver, which is distance-based, and is not varying because the nodes are not moving.

The ECDF of the signals received by AP1 and AP2 are given below.

Figure *ECDF of the signals received by AP1 for the Residential Scenario*. illustrates the ECDF of the signals received by AP1 for the Residential Scenario.

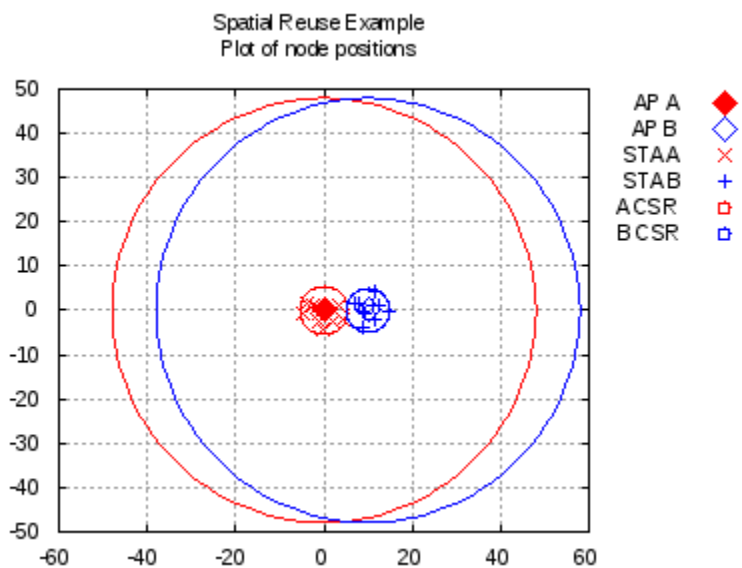


Fig. 4.14: Node positions for the Residential Scenario.

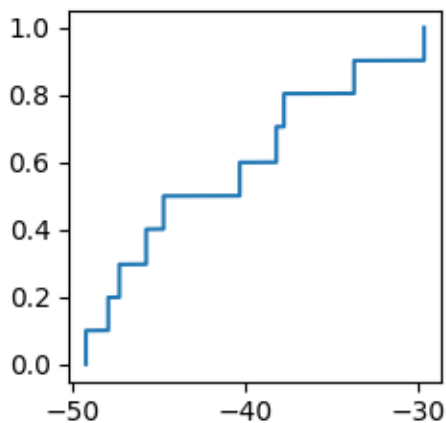


Fig. 4.15: ECDF of the signals received by AP1 for the Residential Scenario.

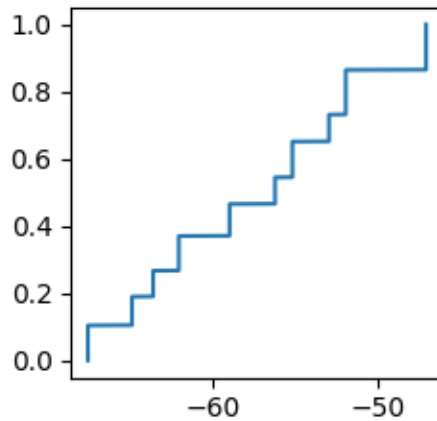


Fig. 4.16: ECDF of the signals received by AP2 for the Residential Scenario.

Figure *ECDF of the signals received by AP2 for the Residential Scenario*. illustrates the ECDF of the signals received by AP2 for the Residential Scenario.

It is observed that the distribution of the signal levels from the 10 randomly positioned STAs is almost linear, although there is a larger concentration of signal levels in the range of approximately -58 to -53 dB.

The ECDF of the noise levels received by AP1 and AP2 are given below.

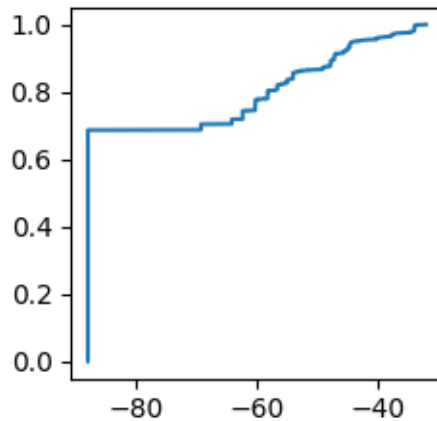


Fig. 4.17: ECDF of the noise level received by AP1 for the Residential Scenario.

Figure *ECDF of the noise level received by AP1 for the Residential Scenario*. illustrates the ECDF of the noise levels received by AP1 for the Residential Scenario.

Figure *ECDF of the noise level received by AP2 for the Residential Scenario*. illustrates the ECDF of the noise levels received by AP2 for the Residential Scenario.

It is observed that the distribution of the noise levels shows that noise levels are predominantly low, with greater than 80% of the time that a packet is received, the noise level being approximately -86 dB (BW = 80 MHz).

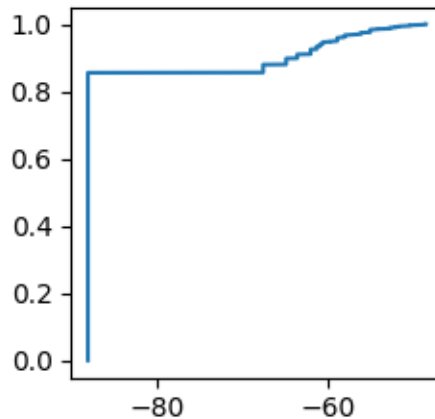


Fig. 4.18: ECDF of the noise level received by AP2 for the Residential Scenario.

Test 2 - Enterprise Scenario

The enterprise scenario is derived from a “wireless office” environment described by STA clusters (cubicles) with APs positioned to service them.

The scenario is simulated in ns-3 as follows: 2 APs are placed $d=10\text{m}$ apart, each with $n=100$ STAs that are dropped within a circle of $r=5\text{m}$ around the AP.

Traffic flow is modelled as a total aggregated offered load of 10 Mbps of uplink traffic only. With a total uplink load of 10 Mbps and $n=100$ STAs per network, the uplink load per STA is $10\text{ Mbps} / 100\text{ nodes} = 0.1\text{ Mbps}$ per STA. Note that this load is a deviation from the scenario as documented in [TGax15], in which different traffic models are assigned separately to each AP.

The enterprise path loss model is given by:

Pathloss model

$$PL(d) = 40.05 + 20 \cdot \log_{10}(f_c/2.4) + 20 \cdot \log_{10}(\min(d, 10)) + (d > 10) * 35 \cdot \log_{10}(d/10) + 7 \cdot W$$

where:

– $d = \max(3D\text{-distance [m]}, 1)$

– $f_c = \text{frequency [GHz]}$

– $W = \text{number of office walls traversed in x-direction plus number of office walls traversed in y-direction}$

This pathloss model is modelled in ns-3 using the `Ieee80211axIndoorPropagationLoss` model with attribute values “DistanceBreakPoint” = 10, “Walls” = 1, and “WallsFactor” = 7.

The following parameters further refine the Enterprise Scenario from the common parameters.

- `test = TGax-test2`
- `d = 10`
- `r = 5`
- `n = 100`
- `uplink = 10.0`
- `downlink = 0.0`

- txRange = 68
- scenario = enterprise
- duration = 2

Note that the duration is reduced here in order to reduce the clock time to complete the simulation.

Results

The node positions for the Enterprise Scenario are given below.

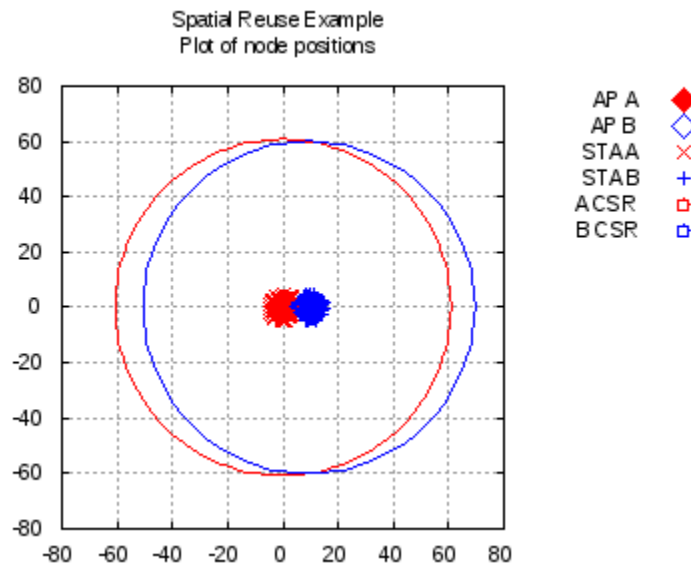


Fig. 4.19: Node positions for the Enterprise Scenario.

Figure *Node positions for the Enterprise Scenario*. illustrates the node positions of the Enterprise Scenario.

We can see a very dense scenario where there are two BSS each with one AP at its center, each with 100 STAs at random position within the $r=5m$ radius about the AP.

The simulation results in throughput of 6.138 Mbps and 5.766 Mbps at AP1 and AP2, respectively. This is 61.38% and 57.66%, respectively, of the 10 Mbps offered load. The results indicate that this simulation scenario saturates the network.

Since each network has a number of sending STAs, an examination of the distribution of signal level and noise levels, from the perspective of the receiving AP, helps provide insight into the behavior of the network on a node-by-node level. The Empirical Cumulative Distribution Function (ECDF) for the signal level and noise levels are provided below, and show that there is variation among the levels.

Steps in the signal and noise level plots indicate transitions in the data that generally correspond to different nodes. For example, the plots below are generated from the scenario with $n=100$ STAs associated per AP, and there are roughly 100 steps. Vertical lines indicate that the signal and noise levels per STA remain constant, which is explained by the deterministic evaluation of the signal at the receiver, which is distance-based, and is not varying because the nodes are not moving.

The ECDF of the signals received by AP1 and AP2 are given below.

Figure *ECDF of the signals received by AP1 for the Enterprise Scenario*. illustrates the ECDF of the signals received by AP1 for the Enterprise Scenario.

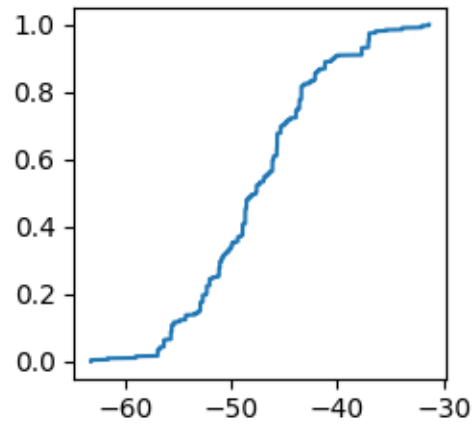


Fig. 4.20: ECDF of the signals received by AP1 for the Enterprise Scenario.

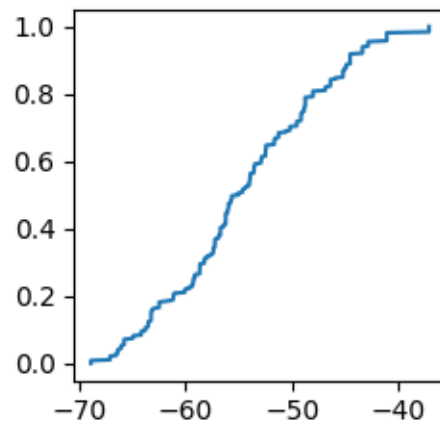


Fig. 4.21: ECDF of the signals received by AP2 for the Enterprise Scenario.

Figure *ECDF of the signals received by AP2 for the Enterprise Scenario*. illustrates the ECDF of the signals received by AP2 for the Enterprise Scenario.

It is observed that the distribution of the signal levels from the 100 randomly positioned STAs is almost linear in the range of -58 to -38 dB

The ECDF of the noise levels received by AP1 and AP2 are given below.

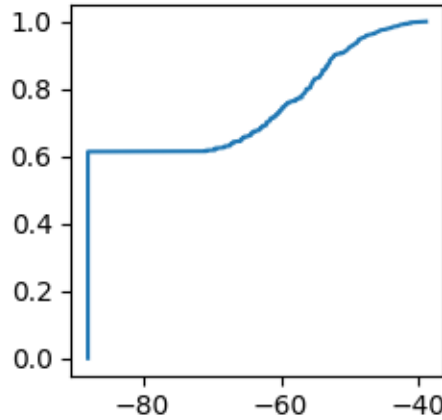


Fig. 4.22: ECDF of the noise level received by AP1 for the Enterprise Scenario.

Figure *ECDF of the noise level received by AP1 for the Enterprise Scenario*. illustrates the ECDF of the noise levels received by AP1 for the Enterprise Scenario.

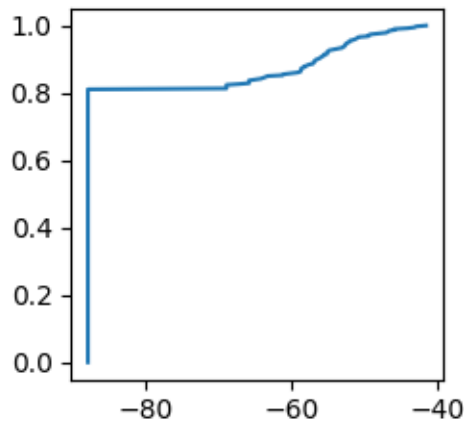


Fig. 4.23: ECDF of the noise level received by AP2 for the Enterprise Scenario.

Figure *ECDF of the noise level received by AP2 for the Enterprise Scenario*. illustrates the ECDF of the noise levels received by AP2 for the Enterprise Scenario.

It is observed that the distribution of the noise levels shows that noise levels are predominantly low, with 60-80% of the time that a packet is received, the noise level being approximately -86 dB (BW = 80 MHz). The remainder of noise levels concentrate in levels above -60 dB.

Test 3 - Indoor Small BSSs Scenario

The indoor small BSSs scenario has the objective to be representative of real-world deployments with high density of APs and STAs [TGax15].

The scenario is simulated in ns-3 as follows: 2 APs are placed $d=34.64\text{m}$ apart, each with $n=30$ STAs that are dropped within a circle of $r=10\text{m}$ around the AP.

This configuration as modelled in this ns-3 scenario is a simplification of the scenario as presented in [TGax15]. Whereas a 19 cell area is outlined in [TGax15], this model only deploys 2 adjacent cells.

Traffic flow is modelled as a total aggregated offered load of 10 Mbps of uplink traffic only. With a total uplink load of 10 Mbps and $n=30$ STAs per network, the uplink load per STA is $10\text{ Mbps} / 30\text{ nodes} = 0.33\text{ Mbps}$ per STA. Note that this load is a deviation from the scenario as documented in [TGax15], in which different traffic models are assigned separately to each BSS.

The Indoor Small BSSs path loss model is given by:

Pathloss model

$$PL(d) = 40.05 + 20 \cdot \log_{10}(f_c/2.4) + 20 \cdot \log_{10}(\min(d, 10)) + (d > 10) * 35 \cdot \log_{10}(d/10)$$

where:

– $d = \max(3\text{D-distance [m]}, 1)$

– $f_c = \text{frequency [GHz]}$

This pathloss model is modelled in ns-3 using the `Ieee80211axIndoorPropagationLoss` model with attribute values “DistanceBreakPoint” = 10, “Walls” = 0, and “WallsFactor” = 0.

The following parameters further refine the Indoor Small BSSs Scenario from the common parameters.

- `test = TGax-test3`
- `d = 34.64`
- `r = 10`
- `n = 30`
- `uplink = 10.0`
- `downlink = 0.0`
- `txRange = 107`
- `scenario = indoor`

Results

The node positions for the Indoor Small BSSs Scenario are given below.

Figure *Node positions for the Indoor Small BSSs Scenario* illustrates the node positions of the Indoor Small BSSs Scenario.

We can see a dense scdnario where there are two BSS each with one AP at its center, each with 30 STAs at random position within the $r=10\text{m}$ radius about the AP.

The simulation results in throughput of 7.434 Mbps and 6.9564 Mbps at AP1 and AP2, respectively. This is 74.34% and 69.56%, respectively, of the 10 Mbps offered load. The results indicate that this simulation scenario saturates the network.

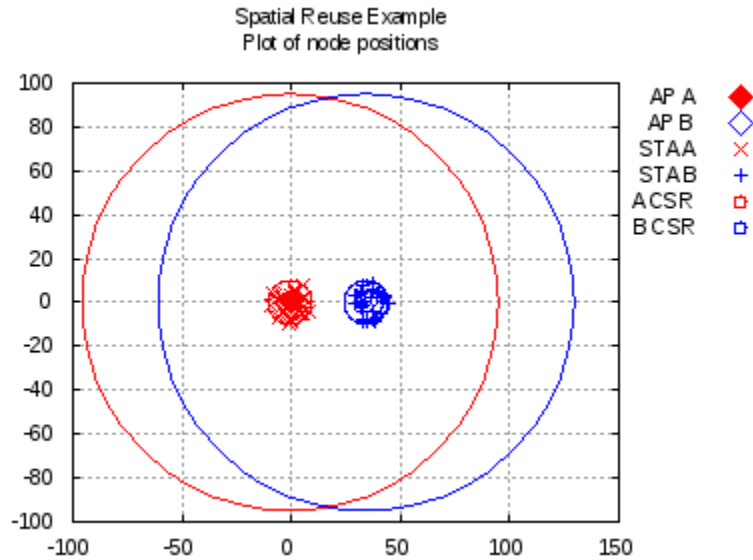


Fig. 4.24: Node positions for the Indoor Small BSSs Scenario.

Since each network has a number of sending STAs, an examination of the distribution of signal level and noise levels, from the perspective of the receiving AP, helps provide insight into the behavior of the network on a node-by-node level. The Empirical Cumulative Distribution Function (ECDF) for the signal level and noise levels are provided below, and show that there is variation among the levels.

Steps in the signal and noise level plots indicate transitions in the data that generally correspond to different nodes. For example, the plots below are generated from the scenario with $n=30$ STAs associated per AP, and there are roughly 30 steps. Vertical lines indicate that the signal and noise levels per STA remain constant, which is explained by the deterministic evaluation of the signal at the receiver, which is distance-based, and is not varying because the nodes are not moving.

The ECDF of the signals received by AP1 and AP2 are given below.

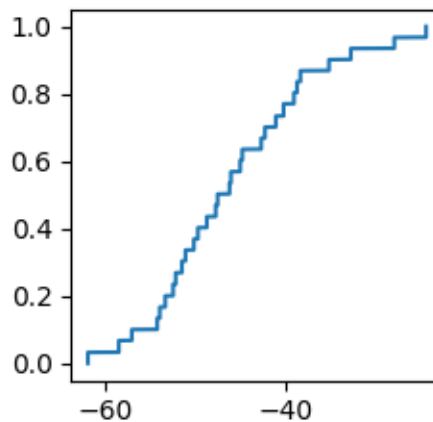


Fig. 4.25: ECDF of the signals received by AP1 for the Indoor Small BSSs Scenario.

Figure *ECDF of the signals received by AP1 for the Indoor Small BSSs Scenario*, illustrates the ECDF of the signals

received by AP1 for the Indoor Small BSSs Scenario.

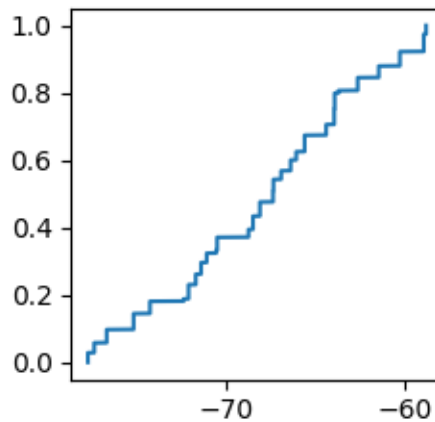


Fig. 4.26: ECDF of the signals received by AP2 for the Indoor Small BSSs Scenario.

Figure *ECDF of the signals received by AP2 for the Indoor Small BSSs Scenario*. illustrates the ECDF of the signals received by AP2 for the Indoor Small BSSs Scenario.

It is observed that the distribution of the signal levels from the 30 randomly positioned STAs is almost linear, although there is a larger concentration of signal levels in the range of approximately -58 to -32 dB.

The ECDF of the noise levels received by AP1 and AP2 are given below.

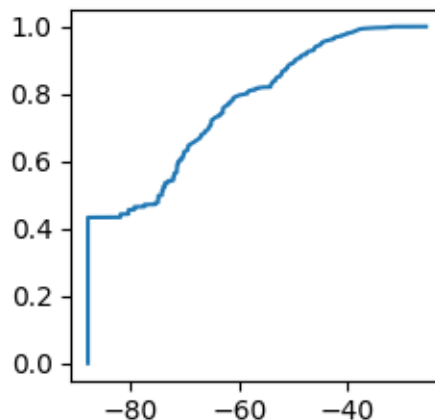


Fig. 4.27: ECDF of the noise level received by AP1 for the Indoor Small BSSs Scenario.

Figure *ECDF of the noise level received by AP1 for the Indoor Small BSSs Scenario*. illustrates the ECDF of the noise levels received by AP1 for the Indoor Small BSSs Scenario.

Figure *ECDF of the noise level received by AP2 for the Indoor Small BSSs Scenario*. illustrates the ECDF of the noise levels received by AP2 for the Indoor BSSs Scenario.

It is observed that the distribution of the noise levels shows that noise levels are predominantly low, with 60-80% of the time that a packet is received, the noise level being approximately -86 dB (BW = 80 MHz). The remainder of noise levels concentrate in levels above -60 dB.

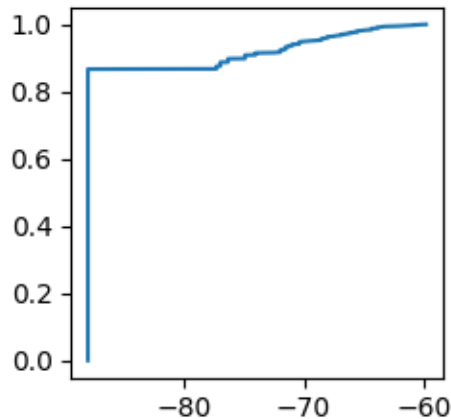


Fig. 4.28: ECDF of the noise level received by AP2 for the Indoor Small BSSs Scenario.

Test 4 - Outdoor Small BSS Scenario

The outdoor small BSS scenario has the objective to be representative of real-world outdoor deployments with a high separation between APs (BSS edge with low SNR) with high density of STAs [TGax15].

The scenario is simulated in ns-3 as follows: 2 APs are placed $d=130\text{m}$ apart, each with $n=50$ STAs that are dropped within a circle of $r=70\text{m}$ around the AP.

This configuration as modelled in this ns-3 scenario is a simplification of the scenario as presented in [TGax15]. Whereas a 19 cell area is outlined in [TGax15], this model only deploys 2 adjacent cells.

Traffic flow is modelled as a total aggregated offered load of 10 Mbps of uplink traffic only. With a total uplink load of 10 Mbps and $n=50$ STAs per network, the uplink load per STA is $10\text{ Mbps} / 50\text{ nodes} = 0.20\text{ Mbps per STA}$. Note that this load is a deviation from the scenario as documented in [TGax15], in which different traffic models are assigned separately to each BSS.

The Outdoor Small BSS path loss model is given in [TGax15] for LOS and NLOS conditions.

This pathloss model is modelled in ns-3 using the `ItuUmiPropagationLoss` model.

The following parameters further refine the Outdoor Large BSS Scenario from the common parameters.

- `test = TGax-test4`
- `d = 130`
- `r = 70`
- `n = 50`
- `uplink = 10.0`
- `downlink = 0.0`
- `txRange = 50`
- `scenario = indoor`

Results

The node positions for the Outdoor Large BSS Scenario are given below.

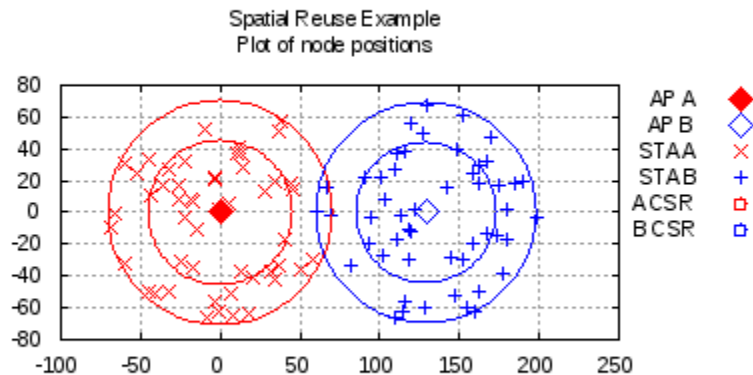


Fig. 4.29: Node positions for the Outdoor Large BSS Scenario.

Figure *Node positions for the Outdoor Large BSS Scenario*. illustrates the node positions of the Outdoor Large BSS Scenario.

We can see a dense scenario where there are two BSS each with one AP at its center, each with 50 STAs at random position within the $r=70\text{m}$ radius about the AP.

The simulation results in throughput of 5.8104 Mbps and 5.6664 Mbps at AP1 and AP2, respectively. This is 58.10% and 56.66%, respectively, of the 10 Mbps offered load. The results indicate that this simulation scenario saturates the network.

Since each network has a number of sending STAs, an examination of the distribution of signal level and noise levels, from the perspective of the receiving AP, helps provide insight into the behavior of the network on a node-by-node level. The Empirical Cumulative Distribution Function (ECDF) for the signal level and noise levels are provided below, and show that there is variation among the levels.

Steps in the signal and noise level plots indicate transitions in the data that generally correspond to different nodes. For example, the plots below are generated from the scenario with $n=50$ STAs associated per AP, and there are roughly 10 steps. Vertical lines indicate that the signal and noise levels per STA remain constant, which is explained by the deterministic evaluation of the signal at the receiver, which is distance-based, and is not varying because the nodes are not moving.

The ECDF of the signals received by AP1 and AP2 are given below.

Figure *ECDF of the signals received by AP1 for the Outdoor Large BSS Scenario*. illustrates the ECDF of the signals received by AP1 for the Outdoor Large BSS Scenario.

Figure *ECDF of the signals received by AP2 for the Outdoor Large BSS Scenario*. illustrates the ECDF of the signals received by AP2 for the Outdoor Large BSS Scenario.

It is observed that the distribution of the signal levels from the 50 randomly positioned STAs is almost linear for signal levels above approximately -72 dB.

The ECDF of the noise levels received by AP1 and AP2 are given below.

Figure *ECDF of the noise level received by AP1 for the Outdoor Large BSS Scenario*. illustrates the ECDF of the noise levels received by AP1 for the Outdoor Large BSS Scenario.

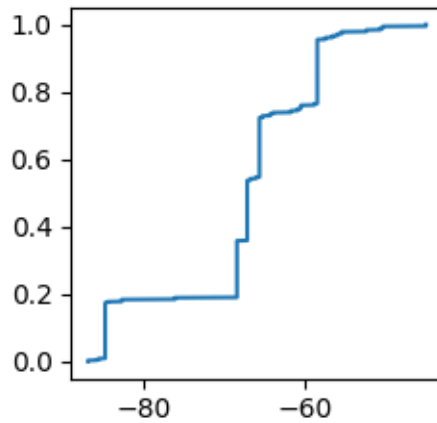


Fig. 4.30: ECDF of the signals received by AP1 for the Outdoor Large BSS Scenario.

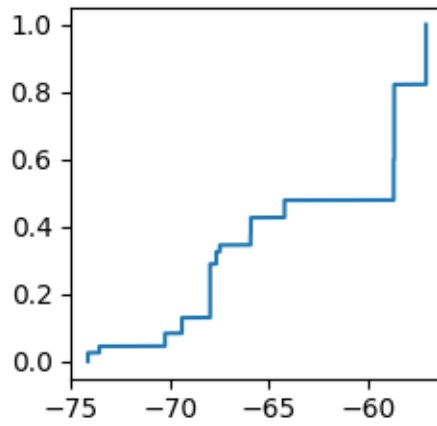


Fig. 4.31: ECDF of the signals received by AP2 for the Outdoor Large BSS Scenario.

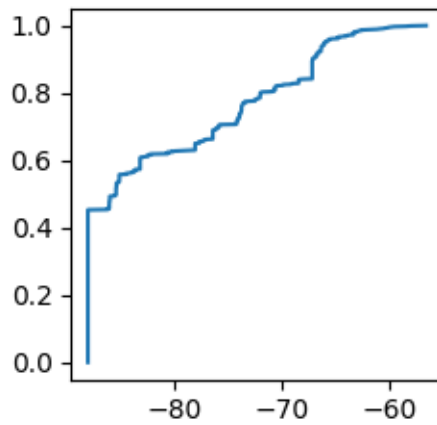


Fig. 4.32: ECDF of the noise level received by AP1 for the Outdoor Large BSS Scenario.

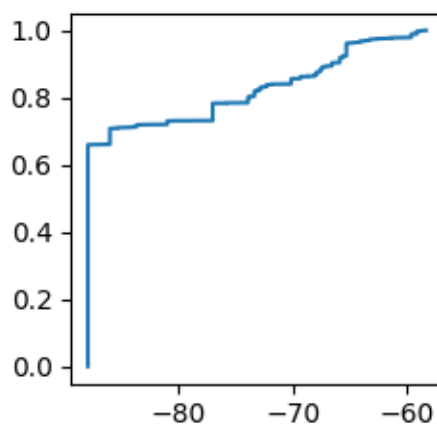


Fig. 4.33: ECDF of the noise level received by AP2 for the Outdoor Large BSS Scenario.

Figure *ECDF of the noise level received by AP2 for the Outdoor Large BSS Scenario*. illustrates the ECDF of the noise levels received by AP2 for the Outdoor BSS Scenario.

It is observed that the distribution of the noise levels shows that noise levels are high, as compared to other scenarios modelled here, with only 40-60% of the time that a packet is received, the noise level being approximately -86 dB (BW = 80 MHz).

RESULTS

Overview

In this chapter we provide simulation results obtained to evaluate the Wi-Fi HE features, especially spatial reuse. We first describe the framework used to launch simulation scenarios and process the results. Then we present the results for some selected scenarios and parametric studies.

Scenario

For this module, we introduce the notion of a scenario. This subsection describes what a scenario is and how to use it.

A scenario refers to a simulation experiment for which a simulation runs is conducted and the data post-processed to yield results such as plots. By varying experiment parameters, several similar scenarios can be run and results among them can be compared as sensitivity studies of those parameters.

A complete scenario is defined by one or more networks. Each network has a single AP, and one or more STAs. The STAs are randomly dropped within a circle centered at the networks AP, and are uniformly distributed within the circle.

Nodes communicate by sending traffic with an offered uplink load (total summation of all traffic from all STAs toward the AP) or downlink load (total summation of load from the AP that is allocated prorata to the STAs).

When more than one network is simulated, the APs are separated from one another by some separation distance.

Key Parameters

The key parameters in defining a network, then, are:

- d - separating distance between each AP
- n - the number of STAs per network
- r - the radius within which the STAs are distributed
- n_{Bss} - the number of networks
- uplink - the total offered load from the STAs towards the AP
- downlink - the total load from the AP towards the STAs

Nomenclature: *d-r-nBss-n-uplink-downlink*

The notation we use to define a scenario takes the form of:

d-r-nBss-n-uplink-downlink

For example, scenario 80-30-02-05-0003-0000 means that the networks are separated by $d=80\text{m}$, with STAs dropped into each network within a radius of $r=30\text{m}$, and there are $nBss=2$ networks each with $n=5$ STAs with a total uplink traffic load of 3 Mbps from the STAs towards the AP and a downlink load of 0 Mbps from the AP towards the STAs.

The behaviors of the network can be evaluated by varying these parameters and measuring the resulting network performance.

As an example evaluation, we run simulations for several scenarios by varying the parameters as follows:

- d - 80, 60, 40, and 20m
- r - 30, 20, and 10m
- nBss - 2 (only two networks, A and B, are enabled)
- n - 5, 10, or 20 STAs
- uplink - 1, 2, 3, 4, 5, or 6 Mbps
- downlink - 0 Mbps

Remarks

The results of these experiments provide insights into the behaviors of the networks as the distances between them, and the number and positioning of the STAs within them are varied.

For example, the effects of spatial reuse can be evaluated by varying the separating distances between networks. As networks are more closely colocated, overlapping nodes from one networks would tend to interfere with the transmissions of other networks, reducing network throughput.

It is also important to note that obtained curves are from only one run. Ideally, they should have been run for multiple runs that have different random seed. Due to the large amount of time needed to generate those plots, it was decided to limit to a single run, with ns-3 RngRun set to 1. One consequence of this is that curves might show some small irregularities.

Performance Measures

Performance evaluation of the simulations can be evaluated in terms of metrics, such as:

throughput - the amount of packets successfully received at the target destinations, measured in Mbps. Throughput is calculated over the period of time specified by the spatial-reuse script parameter `-duration`. The counting of successfully received packets starts after the network reaches a steady state, and after the ADDBA exchanges across all links have been successfully established.

Throughput is a common term used in network performance evaluations. However, throughput alone does not completely capture the effects of spatial reuse features. For example, if networks A and B both give a throughput of 2 Mbps, this alone does not reflect the number and location of nodes within each network. Thus, a metric of density complementary to throughput helps to describe the network performance.

We consider further two additional metrics:

1. Area capacity - throughput divided by the area within which the nodes of the network have been placed, measured in Mbps / m².

2. Area spectrum efficiency - throughput per Hertz divide by the area within which the nodes of the network have been placed, measured in Mbps / Hz / m².

Airtime utilization will also be plotted for parametric studies.

Examples of these metrics with further explanation are given below.

Example Scenarios

As an example comparison, we consider two of these scenarios:

1. Scenario 80-30-02-20 and
2. Scenario 20-10-02-05

The first scenario separates the two networks by a distance of 80m, and places 20 nodes within a radius of 30m around each AP, while the second scenario reduces the AP separation to 20m and also reduces the number of STAs and the radius into which they are positioned.

Scenario 80-30-02-20

In this scenario, two networks (A and B) each have one AP that are placed 80m apart. Each network has 20 STAs dropped within a radius of 30m from the AP.

The node positions for the 80-30-02-20 scenario is given below.

Figure *Node positions for the 80-30-02-20 experiment*. illustrates the node positions of the 80-30-02-20 scenario.

We can see that each network is separated by distance such that interference between networks should be minimized. We would expect each network to behave similarly, and that communications effect between them would not generally impact their performance, as, for example, the offered load is increased and the networks reach saturation levels.

Throughput (AP1 only)

The throughput as offered load is increased is shown below for AP1 (network A).

Figure *Throughput for AP1 for the 80-30-02-20 experiment*. illustrates the throughput for AP1.

It is observed that the network reaches a throughput saturation of approximately 4.5 Mbps.

Throughput (AP2 only)

The throughput as offered load is increased is shown below for AP2 (network B).

Figure *Throughput for AP2 for the 80-30-02-20 experiment*. illustrates the throughput for AP2.

It is observed that the network reaches a throughput saturation of approximately 4.5 Mbps.

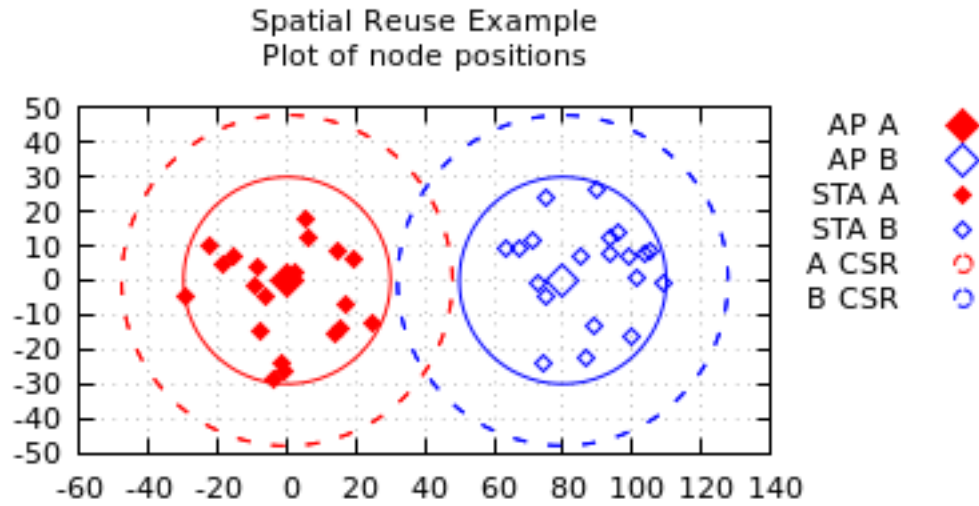


Fig. 5.1: Node positions for the 80-30-02-20 experiment.

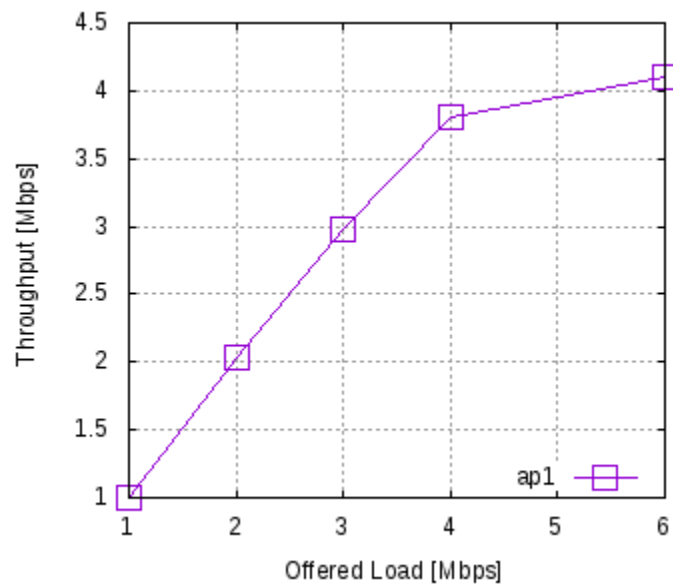


Fig. 5.2: Throughput for AP1 for the 80-30-02-20 experiment.

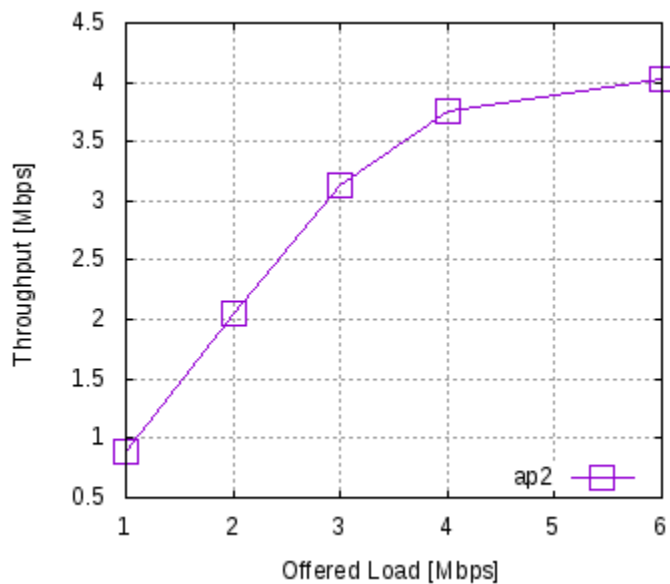


Fig. 5.3: Throughput for AP2 for the 80-30-02-20 experiment.

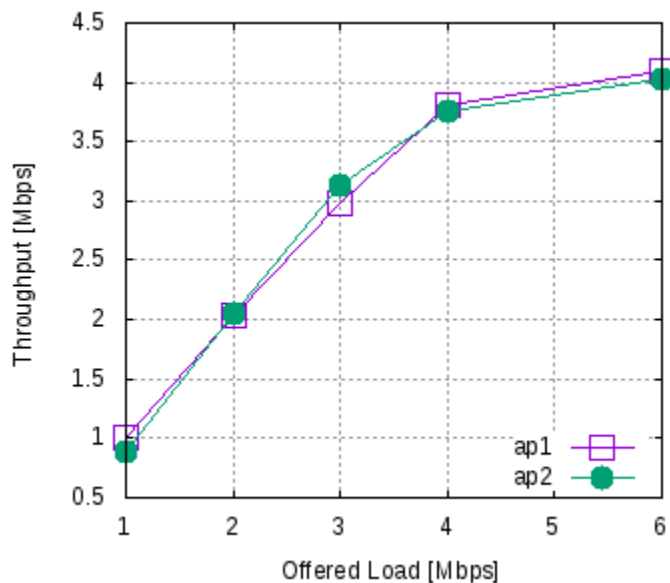


Fig. 5.4: Throughput for AP1 and AP2 for the 80-30-02-20 experiment.

Throughput (Both AP1 and AP2 on a single plot)

Both plots are combined into one single plot below.

Figure *Throughput for AP1 and AP2 for the 80-30-02-20 experiment*. illustrates the throughput for AP1 and AP2.

By combining system throughput for both networks onto a single plot, it is easier to observe that the both networks perform similarly and reach a throughput saturation of approximately 4.5 Mbps.

Area Capacity (Both AP1 and AP2 on the same plot)

The area capacity for both networks is plotted on a single plot below.

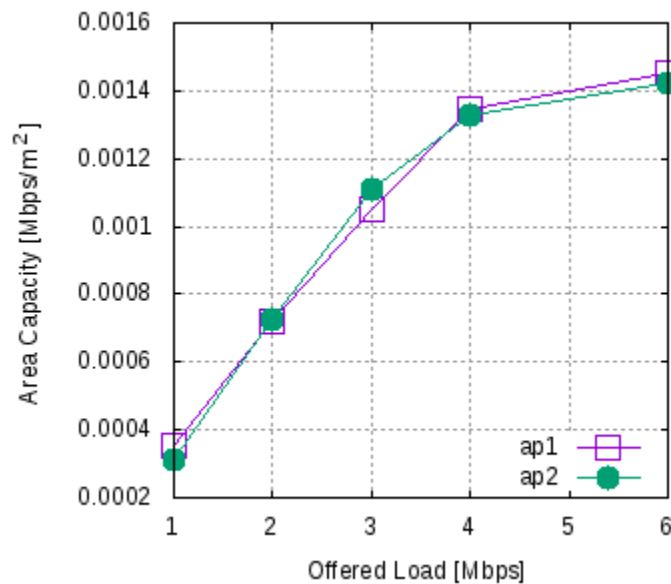


Fig. 5.5: Area capacity for AP1 and AP2 for the 80-30-02-20 experiment.

Figure *Area capacity for AP1 and AP2 for the 80-30-02-20 experiment*. illustrates the area capacity for AP1 and AP2.

It is observed that the shapes of the curves in the area capacity plots generally follow the corresponding shapes of the throughput curves for these two networks. This is because the areas are identical for both networks into which the nodes have been placed.

Area Spectrum Efficiency (Both AP1 and AP2 on the same plot)

The area spectrum efficiency for both networks is plotted on a single plot below.

Figure *Area spectrum efficiency for AP1 and AP2 for the 80-30-02-20 experiment*. illustrates the area spectrum efficiency for AP1 and AP2.

It is observed that the shapes of the curves in the area spectrum efficiency plots generally follow the corresponding shapes of the throughput curves for these two networks. This is because the areas are identical for both networks into which the nodes have been placed, and the operating frequency (in Hz) is also identical for both networks, which simulate 802.11ac networks.

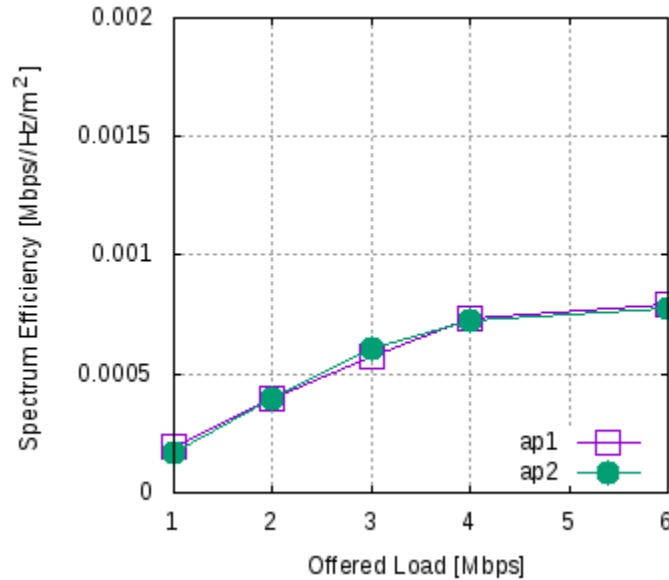


Fig. 5.6: Area spectrum efficiency for AP1 and AP2 for the 80-30-02-20 experiment.

Scenario 20-10-02-05

This scenario differs from the previous one by reducing the separation distance between the two APs, reducing the number of STAs per BSS, and reducing the radius into which the STAs are placed near their corresponding AP. While several variables are thus changed, the evaluation of the scenario provides a comparison of performance between two different scenario configurations.

In this scenario, two networks (A and B) each have one AP that are placed 20m apart. Each network has 5 STAs dropped within a radius of 10m from the AP.

The node positions for the 20-10-02-05 scenario is given below.

Figure *Node positions for the 20-10-02-05 experiment* illustrates the node positions.

In contrast to the 80-30-02-20 scenario, we can see that each network is separated by a shorter distance such that interference between networks may occur. We might expect communications effects between them would impact their performance, as, for example, the offered load is increased and the networks reach saturation levels.

Throughput (Both AP1 and AP2 on the same plot)

The throughput as offered load is increased is shown below for both networks.

Figure *Throughput for AP1 for the 20-10-02-05 experiment* illustrates the throughput for AP1 and AP2.

It is observed that the networks reach a throughput saturation of approximately 2.8 Mbps. This is a much lower throughput than in the earlier example where the APs were at a greater separation distance (80m vs. 20m), even though the number of STAs in each network was also greater (20 vs. 5). In effect, the closer proximity of the nodes and the overlap of the networks degrades communications effectiveness, as indicated by the reduced throughput.

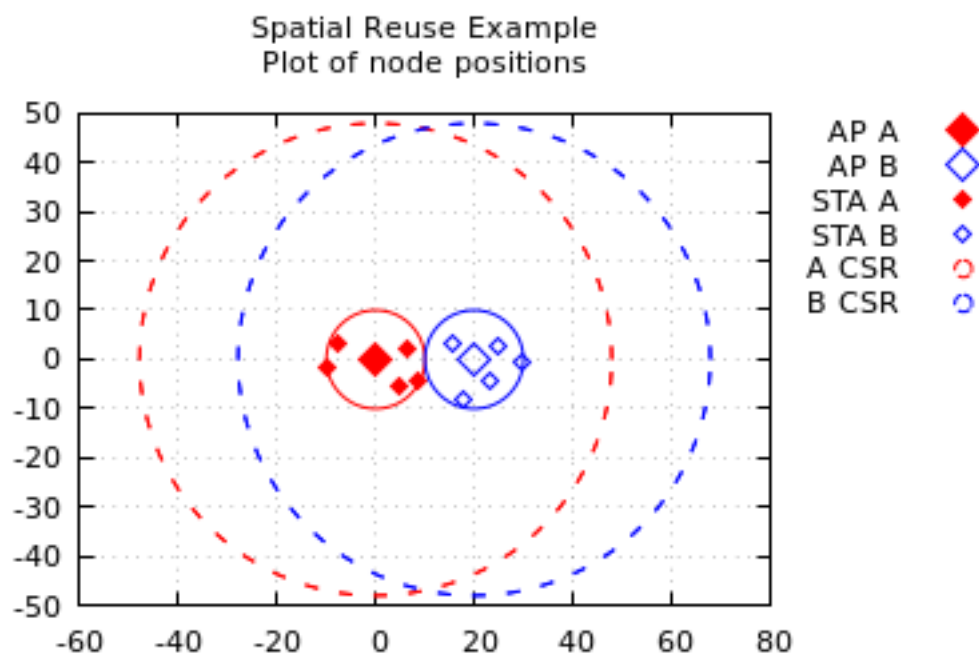


Fig. 5.7: Node positions for the 20-10-02-05 experiment.

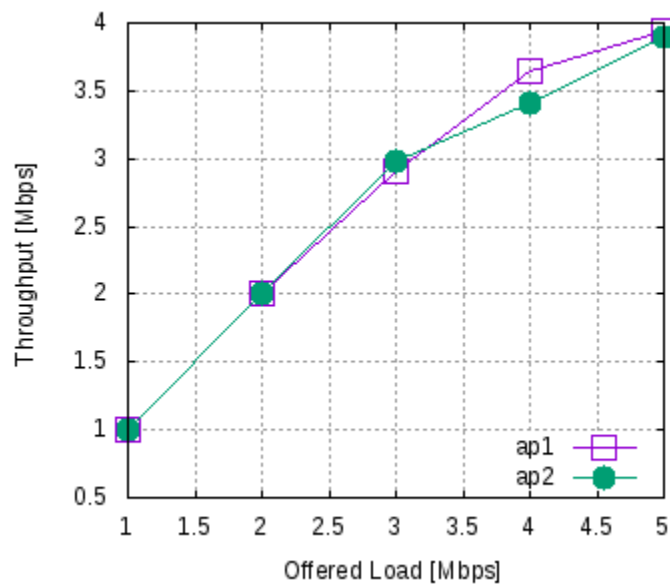


Fig. 5.8: Throughput for AP1 for the 20-10-02-05 experiment.

Area Capacity (Both AP1 and AP2 on the same plot)

The area capacity for both networks is plotted on a single plot below.

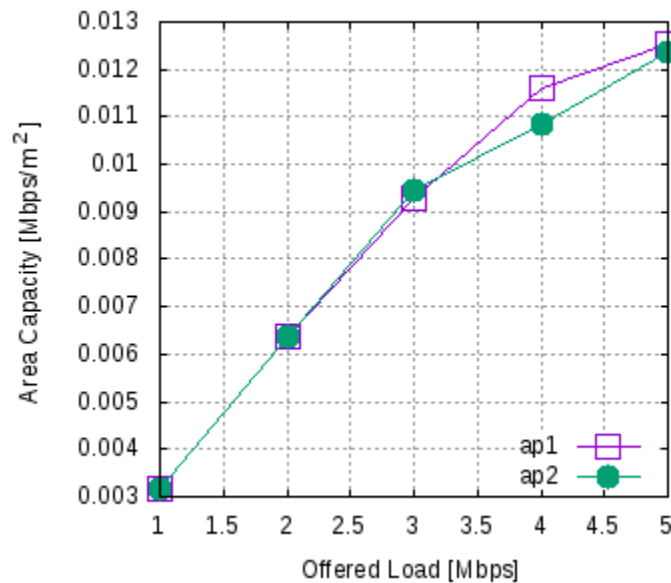


Fig. 5.9: Area capacity for AP1 and AP2 for the 20-10-02-05 experiment.

Figure *Area capacity for AP1 and AP2 for the 20-10-02-05 experiment*. illustrates the area capacity for AP1 and AP2.

It is observed that the shapes of the curves in the area capacity plots generally follow the corresponding shapes of the throughput curves for these two networks. This is because the areas are identical for both networks into which the nodes have been placed.

Area Spectrum Efficiency (Both AP1 and AP2 on the same plot)

The area spectrum efficiency for both networks is plotted on a single plot below.

Figure *Area spectrum efficiency for AP1 and AP2 for the 20-10-02-05 experiment*. illustrates the area spectrum efficiency for AP1 and AP2.

It is observed that the shapes of the curves in the area spectrum efficiency plots generally follow the corresponding shapes of the throughput curves for these two networks. This is because the areas are identical for both networks into which the nodes have been placed, and the operating frequency (in Hz) is also identical for both networks, which simulate 802.11ac networks.

Area Capacity (Both Scenarios)

In order to show an example of the performance comparison between the two scenarios, the area capacity for both scenarios is plotted on a single plot below.

Figure *Area capacity for scenarios 80-30-02-20 and 20-10-02-05*. illustrates the area capacity for both scenarios.

It is observed that the scenario 80-30-02-20 has a significantly higher area capacity than the 20-10-02-05 scenario.

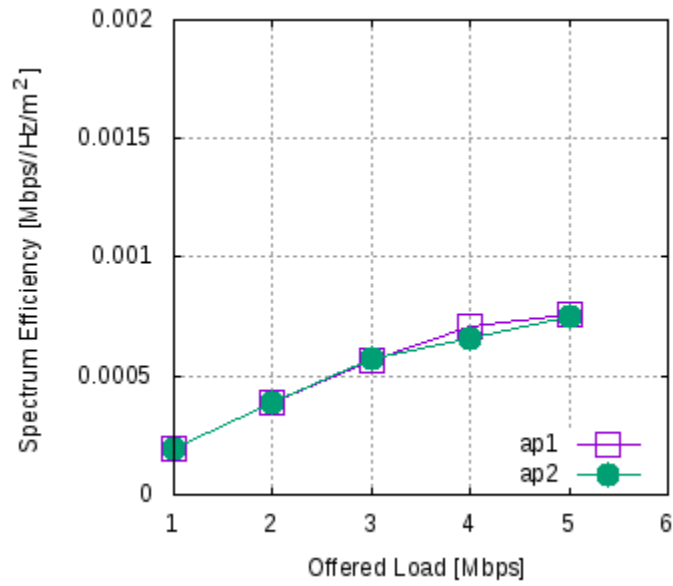


Fig. 5.10: Area spectrum efficiency for AP1 and AP2 for the 20-10-02-05 experiment.

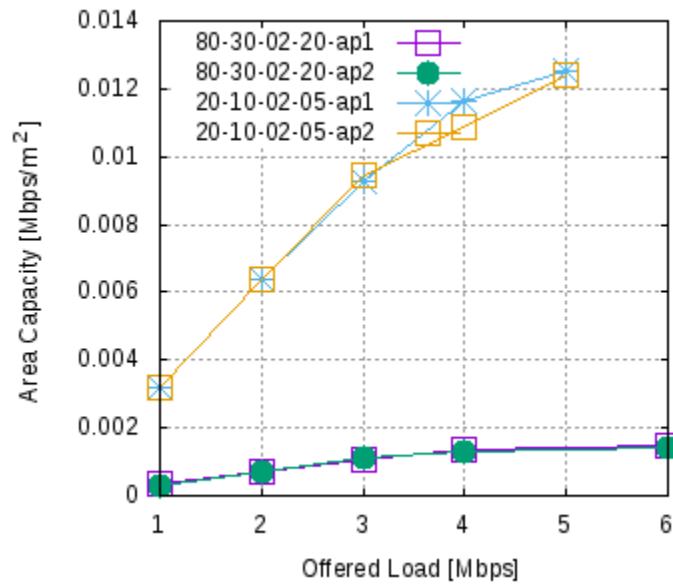


Fig. 5.11: Area capacity for scenarios 80-30-02-20 and 20-10-02-05.

Sensitivity Analysis

This section presents results of the sensitivity of key parameters (distance, radius, and number of nodes per network) to the resulting area capacity, for scenarios with two BSSs.

Distance Sensitivity

The area capacity for several scenarios is plotted on a single plot below. The selected scenarios use the same values of $r=20$, $n_{Bss}=2$, and $n=10$, while varying the distance, $d=\{20, 40, 60, 80\}$.

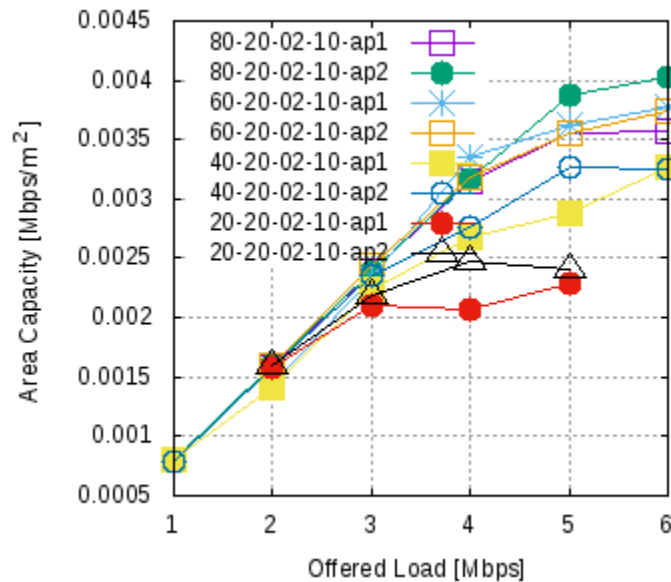


Fig. 5.12: Area capacity for scenarios where the distance between APs varies.

Figure *Area capacity for scenarios where the distance between APs varies*. illustrates the area capacity for scenarios where the distance varies.

It is observed that area capacity decreases as the distances between APs decreases. In effect, the closer that the two APs are to one another, the more likely there is to be collisions among transmitting nodes that reduces performance for both networks.

Dropping Radius Sensitivity

The area capacity for several scenarios is plotted on a single plot below. The selected scenarios use the same values of $d=80$, $n_{Bss}=2$, and $n=10$, while varying the dropping radius, $r=\{10, 20, 30\}$.

Figure *Area capacity for scenarios where the dropping radius for the positioning of STAs varies*. illustrates the area capacity for scenarios where the radius varies.

It is observed that area capacity increases as the radius decreases. In effect, for the parametric sensitivities given here, the closer that the same number of nodes are placed to their AP thus reduces the transmission collisions of one network with its neighboring network, resulting in increased performance.

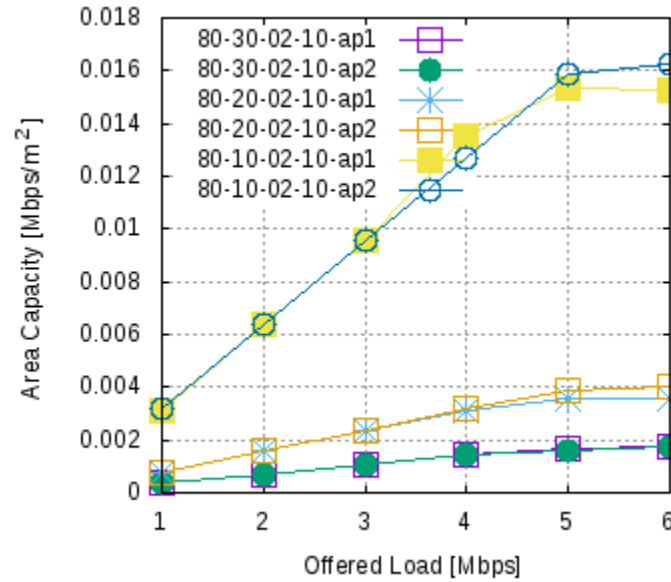


Fig. 5.13: Area capacity for scenarios where the dropping radius for the positioning of STAs varies.

Number of STAs Sensitivity

The area capacity for several scenarios is plotted on a single plot below. The selected scenarios use the same values of $d=80$, $r=20$, and $n_{BSS}=2$, while varying the number of STAs, $n=\{5, 10, 20\}$.

Figure *Area capacity for scenarios where the number of STAs per network varies* illustrates the area capacity for scenarios where the number of STAs varies.

It is observed that the impact to area capacity is negligible when the network is not saturated. As the network reaches saturation, the area capacity generally increases as the number of STAs per network increases.

Parametric Studies

In the next sections, we discuss parametric studies that have been conducted to examine the behaviors of the spatial reuse feature of 802.11ax. We first describe the framework used to represent the scenarios in order to conduct simulation experiments for these studies. Then we present the results of those studies.

The following three parametric studies are conducted:

- Study 1 – All nodes operate as 802.11ac (baseline)
- Study 2 – All nodes operate as 802.11ax with OBSS_PD features enabled.

Study 1 - 802.11ac (baseline)

The objective of the configuration of this scenario is “to capture the issues and be representative of real-world deployments with high density of APs and STAs” [TGax15].

This simulation study configures the node placements and network simulation parameters according to those defined in [TGax15] (see Scenario 3 - Indoor BSSs Scenario). However, to collect baseline measures, Study 1 configures all nodes to operate in 802.11ac mode, whereas Study 2 evaluates 802.11ax features.

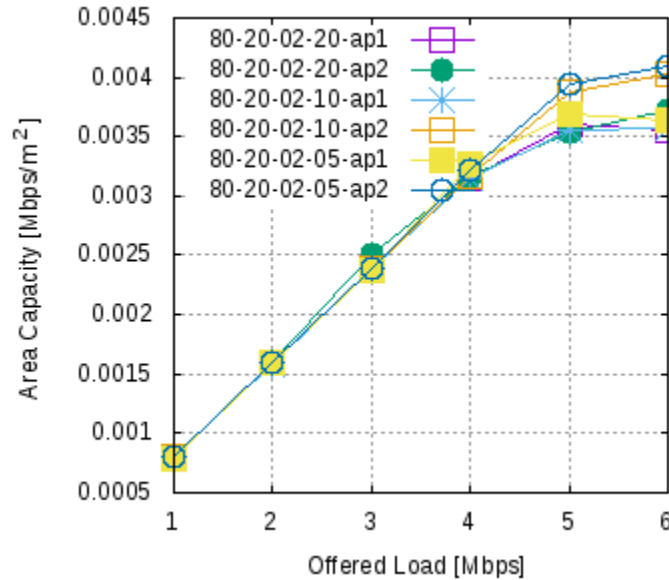


Fig. 5.14: Area capacity for scenarios where the number of STAs per network varies.

Topology / Environment Description

BSSs are placed on a regular and symmetric grid with a reuse frequency of $N=7$.

The node positions for $n=5$ STAs per BSS in Study 1 are given below.

Figure *Node positions for $n=5$ STAs per BSS in Study 1* illustrates the node positions for $n=5$ STAs per BSS in Study 1.

The BSSs are arranged with one BSS of high interest centered in the topology, with six other BSSs surrounding the high-interest BSS and arranged in a hexagonal pattern. As outlined in [TGax15] for the Indoor Small BSSs Scenario, STAs are associated with each BSS within a radius of $r=10\text{m}$.

The figure shown illustrates a scenario in which each BSS has 5 STAs allocated randomly within its dropping radius (solid lines). Dashed lines indicate nominal Carrier Sense Range (CSR) limits of 15m.

Parameters

In this section, we describe the parameters used for Study 1, and we describe any deviations from those described in [TGax15] Scenario 3.

Topology

- BSSs - BSSs are placed in a regular and symmetric grid as shown in the Figure above, with reuse frequency $N=7$. Each hexagon of the grid is modeled as a circle with radius $r=10\text{m}$ into which the positions of the STAs are uniformly distributed.
- Reuse Frequency - $N=7$.
- AP location - APs are placed at the center of each circle.
- Inter BSS Distance (ICD) - BSSs are separated from one another by an inter BSS distance (ICD) of $2 * h$, where $h = \sqrt{r^2 - r^2/4} = 17.32\text{m}$.

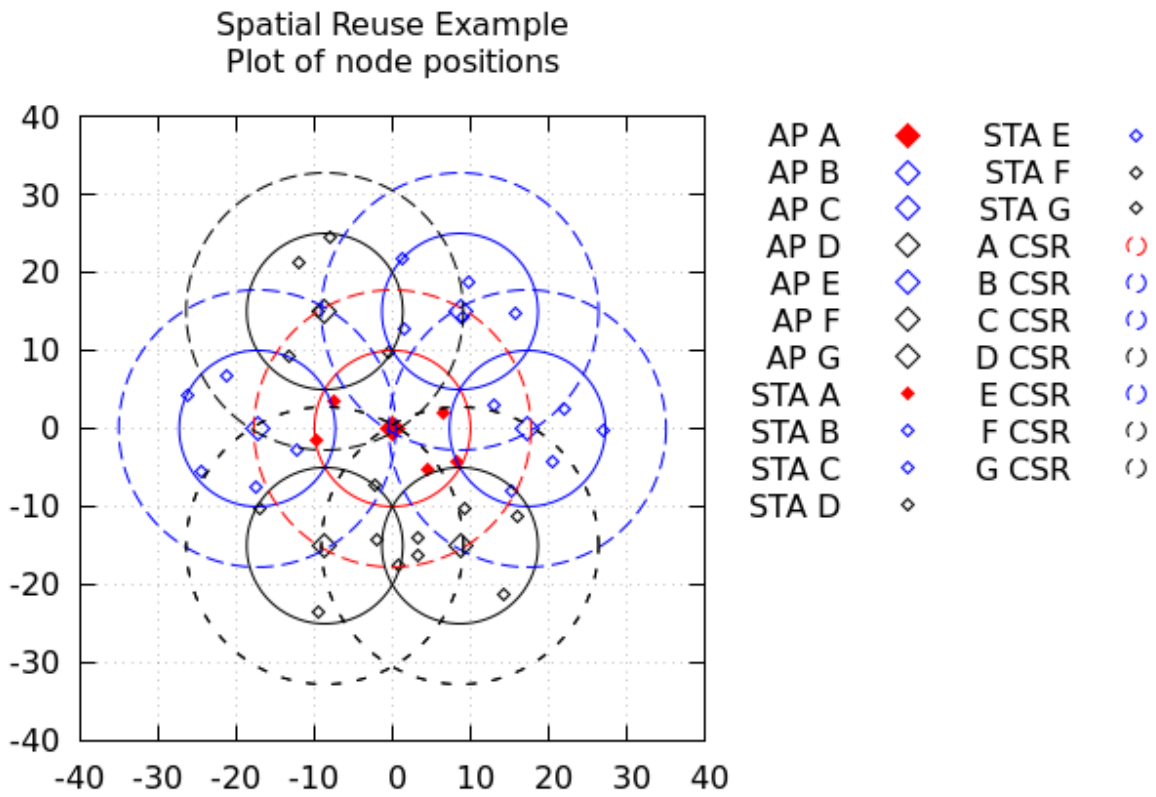


Fig. 5.15: Node positions for n=5 STAs per BSS in Study 1.

- AP antenna height - a 2D model is assumed, and heights of nodes, including the AP antenna height, are not modeled.
- STA locations - STAs are uniformly distributed throughout the circle (radius r) of each BSS.
- Number of STAs - the number of STAs is varied for this study from 5 to 40 in steps of 5.

Channel Model

- Fading model - the TGac channel model D NLOS as mentioned in [TGax15] is not modeled in this study.
- Pathloss model - the pathloss model as given in [TGax15] for the Indoor Small BSSs (Scenario 3) is modeled.
- Shadowing - Log-normal with 5 dB standard deviation, iid across all links.

PHY Parameters

- AP TX power - 20 dBm per antenna.
- STA TX power - 15 dBm per antenna.
- MCS - the ns-3 ideal rate manager is used. This is a minor deviation from the [TGax15] described scenario of MCS0 or MCS7 only.
- Antennas - (SISO) one antenna is modeled per AP and per STA. This is a deviation from the parameters described in [TGax15].
- TX gain - 0 dB
- RX gain - 0 dB

ns-3 parameters:

- Maximum supported TX spatial streams - 1
- Maximum supported RX spatial streams - 1

MAC Parameters

- Access protocol parameters - EDCA with default EDCA parameter set.
- Primary channels - All BSS at 5GHz with 20 MHz BSS with reuse 3. Assignment of 20 MHz bands is a deviation from the parameters described in [TGax15].
- Aggregation - A-MPDU aggregation size of up to 65535 bytes.
- RTS/CTS Threshold - no RTS/CTS.
- Association - STAs are associated with the BSS for the circle into which the STA has been dropped. This varies from the association scheme described in [TGax15], although the resulting number of associated STAs per BSS remains the same.

Traffic Model

The modeling of traffic differs from the approach described in [TGax15], in which several different classes of traffic are described. Instead, an approach is used that allows the mix of uplink and downlink traffic and the packet sizes to be specified.

The total offered load of the entire system is specified in Mbps. This total load is then allocated into uplink and downlink portions. For example, assuming a total offered load of 5.0 Mbps with an allocation of 90% uplink and 10% downlink, then the uplink traffic is $5.0 \times 90\% = 4.5$ Mbps and the downlink traffic is $5.0 \times 10\% = 0.5$ Mbps.

The total load is allocated per node. For example, if the total uplink traffic is 4.5 Mbps and there are 10 STAs, then the traffic flow per link is $4.5 \text{ Mbps} / 10 = 0.45$ Mbps per uplink.

Separate payload sizes (i.e., application layer packet lengths) are specified for the uplink payload and the downlink payload sizes. These payload sizes and the allocated traffic are used to determine the transmission interval per packet.

All traffic is assumed a Constant Bit Rate (CBR) and transmissions use UDP datagrams.

- Uplink payload size - 1500 bytes
- Downlink payload size - 300 bytes

Conducting the Study 1 Experiments

To conduct the experiments for Study 1, a bash script is used to repeatedly run the ns-3 spatial-reuse.cc script.

Parameters are fixed as described above, with the exception of the number of STAs.

The total offered load for each BSS is a balanced load, with the same load for each BSS. The offered load is increased from 1 Mbps to 6 Mbps, in steps of 1 Mbps.

The traffic mix is 90% uplink and 10% downlink, with a uplink payload size of 1500 bytes, and an downlink payload size of 300 bytes.

The number of STAs, n , is varied from 5 to 40 in steps of 5.

All nodes in Study 1 use 802.11ac.

Results are collected in terms of the average of all BSS.

Performance metrics collected include the following (using the same definitions as given earlier):

- system throughput
- area capacity
- area spectrum efficiency
- air-time utilization

To run the Study 1 scenarios, plot results, and transfer those results to the documentation figures, the following scripts should be executed in order:

1. run-spatial-reuse-study1.sh - this generates a script file "study1.sh".
2. study1.sh - this is the script generated by (1), and should be run to generate all results.
3. make-data-files-study1.sh - this creates data files for plotting, from the set of all simulation results.
4. plot-study1.sh - this generates plots of results.
- 5) copy-study1-plots-to-doc-figures.sh - this copies a subset of plots generated into the doc/figures folder, for inclusion of those results into the documentation.

Note that any modifications that are made to change the values of n in the study1 scripts above must be applied to both the 'run-spatial-reuse-study1.sh' script and also the 'plot-study1.sh' script. The first script runs the ns-3 simulations and creates data files that are used by the second script to create plots. Specifically, note that the following items appears in both scripts and thus must be kept synchronized:

```
for n in 5 10 15 20 25 30 35 ; do
```

Note that this line appears once in the ‘run-spatial-reuse-study1.sh’ script and appears several times in the ‘plot-study1.sh’ script because there are several different plots that are produced by the ‘plot-study1.sh’ script from the full set of simulation results that are generated by the ‘run-spatial-reuse-study1.sh’ script.

The values of n that are specified in the ‘plot-study1.sh’ script must be a subset of the values that are specified in the ‘run-spatial-reuse-study1.sh’ script.

Furthermore, changes to the offererdLoad parameter in the ‘run-spatial-reuse-study1.sh’ script may require the axis ranges at the top of the ‘plot-study1.sh’ script to be adjusted.

After the above have been executed, the doc/figures folder should contain the newly generated plots for inclusion in the documentation. The documentation can then be regenerated, e.g.:

```
cd doc
```

```
make latexpdf
```

Study 1 Results

System Throughput

The average upstream throughput as offered load per BSS is increased is shown below. A separate line is plotted for each value of the number of STAs (e.g., $n=5$, $n=10$, $n=15$, ..., $n=40$).

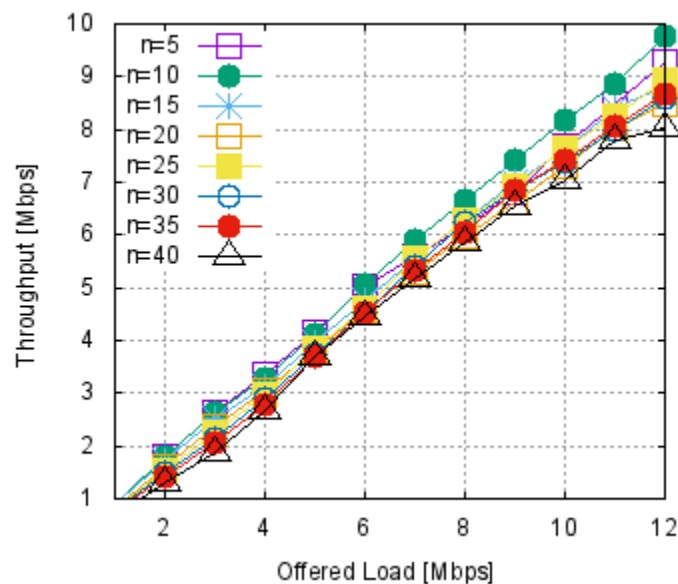


Fig. 5.16: Average upstream throughput for the Study 1 parametric study.

Figure *Average upstream throughput for the Study 1 parametric study* illustrates the average upstream system throughput.

It is observed that the average upstream system throughput increases as offered load increases. Furthermore, upstream system throughput decreases at higher load as the number of STAs, n , per BSS increases. Note that the saturation point is not reached yet at 12 Mbps.

Distribution of Node Contributions to Downlink Throughput

Total throughput of the system is divided into uplink and downlink portions. The downlink portions (from the AP to the STAs) are further divided equally among the STAs. For example, for a total system throughput target of 2 Mbps per BSS that is divided into 90% uplink and 10% downlink, then $2 \text{ Mbps} \times 0.1 = 0.2 \text{ Mbps}$ is allocated to each STA in downlink traffic. If there are 5 STAs in the BSS, then the AP attempts to deliver $0.2 \text{ Mbps} / 5 = 0.04 \text{ Mbps}$ from the AP to each of the 5 STAs. However, when saturated, the packet performance measure of each STA, in terms of actual downlink throughput, may vary from one STA to another.

Area Capacity

The average area capacity as offered load per BSS is increased is shown below. A separate line is plotted for each value of the number of STAs (e.g., $n=5$, $n=10$, $n=15$, ..., $n=40$).

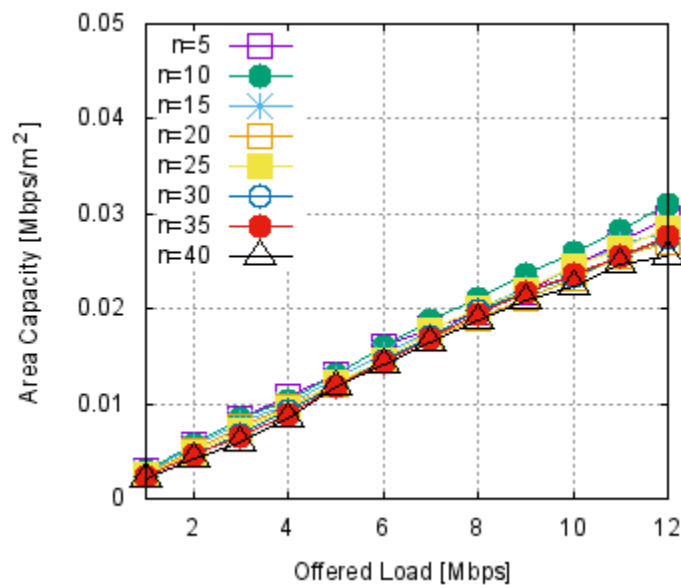


Fig. 5.17: Average area capacity for the Study 1 parametric study.

Figure *Average area capacity for the Study 1 parametric study* illustrates the average system area capacity.

It is observed that the average area capacity increases as offered load increases. Furthermore, area capacity at higher load decreases as the number of STAs, n , per BSS increases.

Area Spectrum Efficiency

The average area spectrum efficiency as offered load per BSS is increased is shown below. A separate line is plotted for each value of the number of STAs (e.g., $n=5$, $n=10$, $n=15$, ..., $n=40$).

Figure *Average area spectrum efficiency for the BSS Study 1 parametric study* illustrates the average system area spectrum efficiency.

It is observed that the average area spectrum efficiency increases as offered load increases. Furthermore, area spectrum efficiency at higher load decreases as the number of STAs, n , per BSS increases.

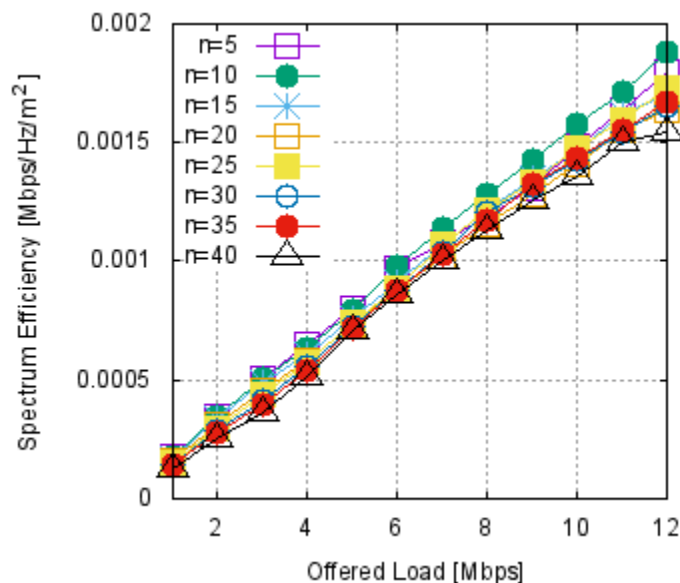


Fig. 5.18: Average area spectrum efficiency for the BSS Study 1 parametric study.

Airtime utilization

The average airtime utilization as offered load per BSS is increased is shown below. A separate line is plotted for each value of the number of STAs (e.g., $n=5$, $n=10$, $n=15$, ..., $n=40$).

Figure *Average airtime utilization for the Study 1 parametric study*. illustrates the average airtime utilization.

Noise and Signal Distributions

The ECDF of the signal level received at the AP of the BSS1 is shown below, for the scenario of $n=20$ nodes, and offered load of 2 Mbps.

Figure *ECDF of the signal level at the AP for the BSS1 in the center of the Study 1 parametric study, with $n=20$ STAs per BSS*. illustrates the ECDF of the signal levels received for BSS1 with $n=20$ STAs per BSS..

The ECDF of the noise level at the AP of the BSS1 is shown below, for the scenario of $n=20$ nodes, and offered load of 2 Mbps.

Figure *ECDF of the signal level at the AP for the BSS1 in the center of the Study 1 parametric study, with $n=20$ STAs per BSS*. illustrates the ECDF of the noise levels at BSS1 with $n=20$ STAs per BSS.

Study 2 - 802.11ax

Study 2 repeats the experiments of Study 1, with the following changes:

- standard - all nodes operate using 802.11ax
- BSS color - each BSS is assigned its own unique color. For example, BSS #1 uses BSS color 1, BSS #2 uses BSS color 2, etc.
- OBSS_PD level - as an additional sensitivity study, this value is varied from -82 dB to -62 dB, in steps of 5 dB.

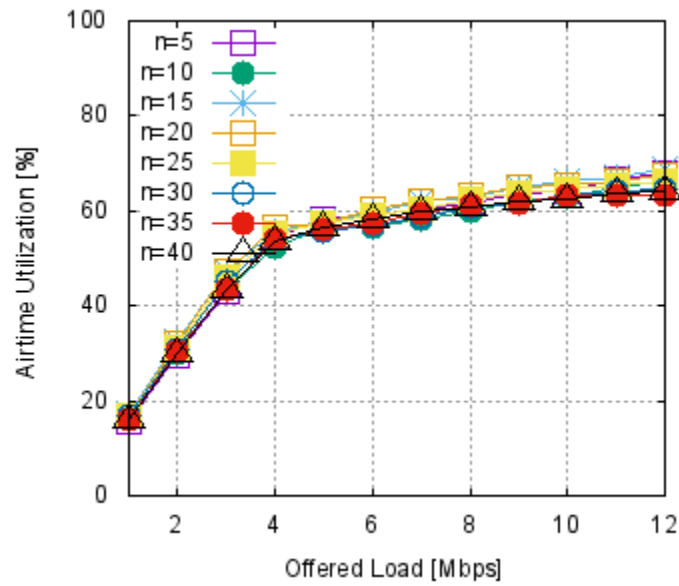


Fig. 5.19: Average airtime utilization for the Study 1 parametric study.

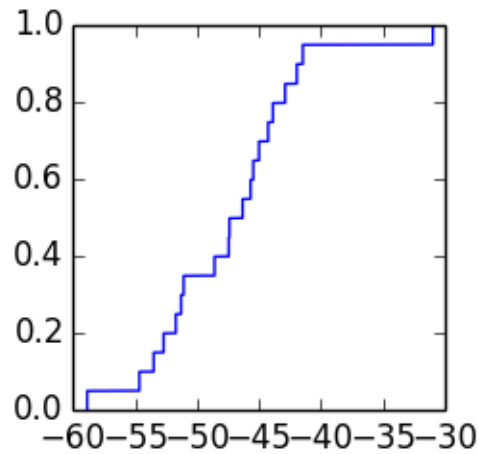


Fig. 5.20: ECDF of the signal level at the AP for the BSS1 in the center of the Study 1 parametric study, with n=20 STAs per BSS.

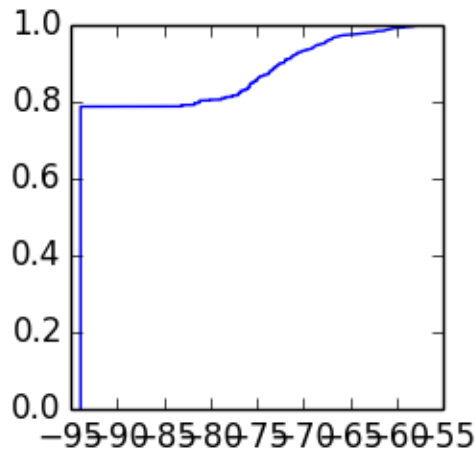


Fig. 5.21: ECDF of the noise level at the AP for the BSS1 in the center of the Study 1 parametric study, with $n=20$ STAs per BSS..

Conducting the Study 2 Experiments

To run the Study 2 scenarios, plot results, and transfer those results to the documentation figures, the following scripts should be executed in order:

1. `run-spatial-reuse-study2.sh` - this generates a script file “`study2.sh`”.
2. `study2.sh` - this is the script generate by (2), and should be run to generate all results.
3. `make-data-files-study2.sh` - this creates data files for plotting, from the set of all simulation results.
4. `plot-study2a.sh` - this generates study2a plots of results (metric under study versus offered load)
5. `plot-study2b.sh` - this generates study2b plots of results. (metric under study versus OBSS_PD level, not presented in this document)
6. `plot-study2-ecdf.sh` - this generates additional plots (ECDFs) from results.
7. `copy-study2-plots-to-doc-figures.sh` - this copies a subset of plots generated into the `doc/figures` folder, for inclusion of those results into the documentation.

After the above have been executed, the `doc/figures` folder should contain the newly generated plots for inclusion in the documentation. The documentation can then be regenerated, e.g.:

```
cd doc
make latexpdf
```

Study 2 Results

System Throughput

The average upstream throughput with OBSS_PD level -82 dBm as offered load per BSS is increased is shown below. A separate line is plotted for each value of the number of STAs (e.g., $n=5$, $n=10$, $n=15$, ..., $n=40$).

Figure *Average upstream throughput with OBSS_PD level -82 dBm for the Study 2 parametric study.* illustrates the average upstream system throughput with OBSS_PD level -82 dBm.

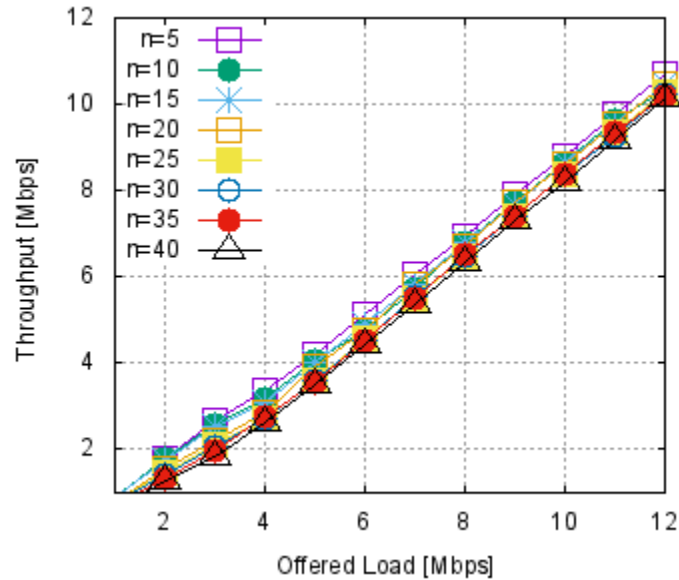


Fig. 5.22: Average upstream throughput with OBSS_PD level -82 dBm for the Study 2 parametric study.

We can observe that study 2 with OBSS_PD level -82 dBm ignores STA transmissions with RSSI lower than -82dBm. Because it sees fewer STAs, the effect of the number of STA induced degradation is lower compared to previous study 1 results.

The average upstream throughput with OBSS_PD level -62 dBm as offered load per BSS is increased is shown below. A separate line is plotted for each value of the number of STAs (e.g., $n=5$, $n=10$, $n=15$, ..., $n=40$).

Figure *Average upstream throughput with OBSS_PD level -62 dBm for the Study 2 parametric study* illustrates the average upstream system throughput with OBSS_PD level -62 dBm.

We notice that results obtained with OBSS_PD level -62 dBm and -82 dBm do not have noticeable difference. This is because the saturation is not reached yet even at 12 Mbit/s.

Area Capacity

The for BSS1.average area capacity with OBSS_PD level -82 dBm as offered load per BSS is increased is shown below. A separate line is plotted for each value of the number of STAs (e.g., $n=5$, $n=10$, $n=15$, ..., $n=40$).

Figure *Average area capacity with OBSS_PD level -82 dBm for the Study 2 parametric study* illustrates the average system area capacity with OBSS_PD level -82 dBm.

The average area capacity with OBSS_PD level -62 dBm as offered load per BSS is increased is shown below. A separate line is plotted for each value of the number of STAs (e.g., $n=5$, $n=10$, $n=15$, ..., $n=40$).

Figure *Average area capacity with OBSS_PD level -62 dBm for the Study 2 parametric study* illustrates the average system area capacity with OBSS_PD level -62 dBm.

Area Spectrum Efficiency

The average area spectrum efficiency with OBSS_PD level -82 dBm as offered load per BSS is increased is shown below. A separate line is plotted for each value of the number of STAs (e.g., $n=5$, $n=10$, $n=15$, ..., $n=40$).

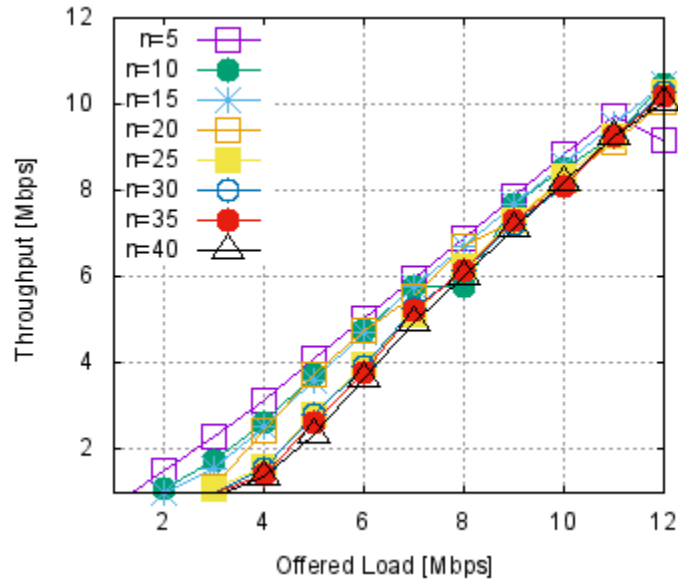


Fig. 5.23: Average upstream throughput with OBSS_PD level -62 dBm for the Study 2 parametric study.

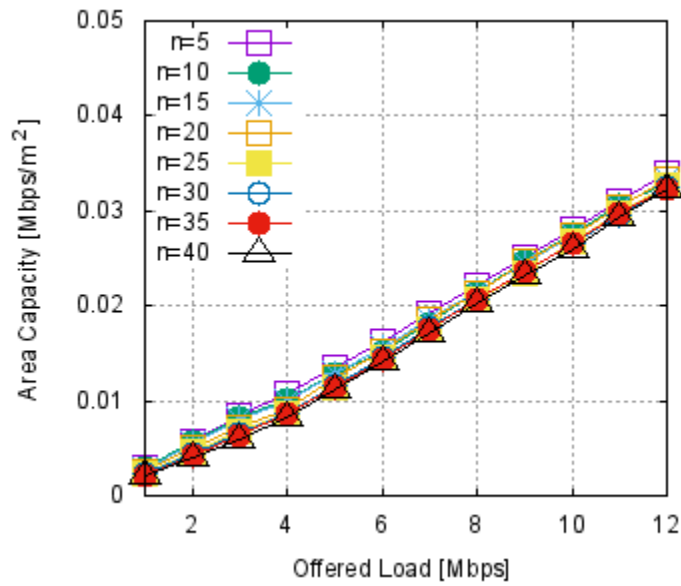


Fig. 5.24: Average area capacity with OBSS_PD level -82 dBm for the Study 2 parametric study.

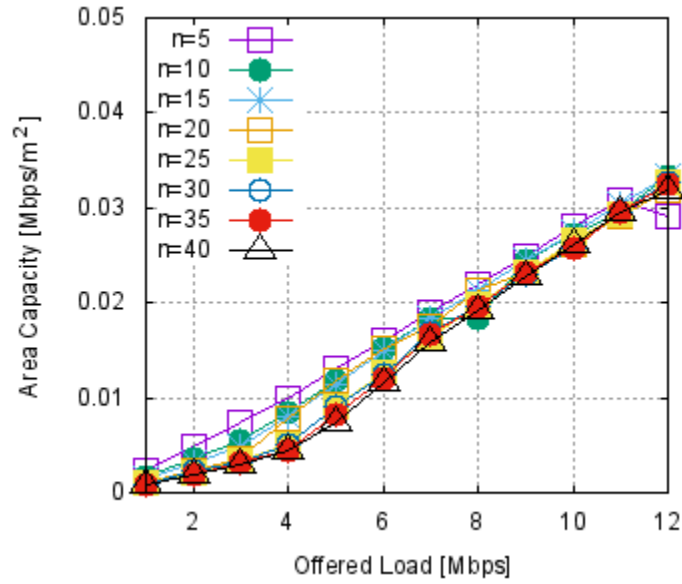


Fig. 5.25: Average area capacity with OBSS_PD level -62 dBm for the Study 2 parametric study.

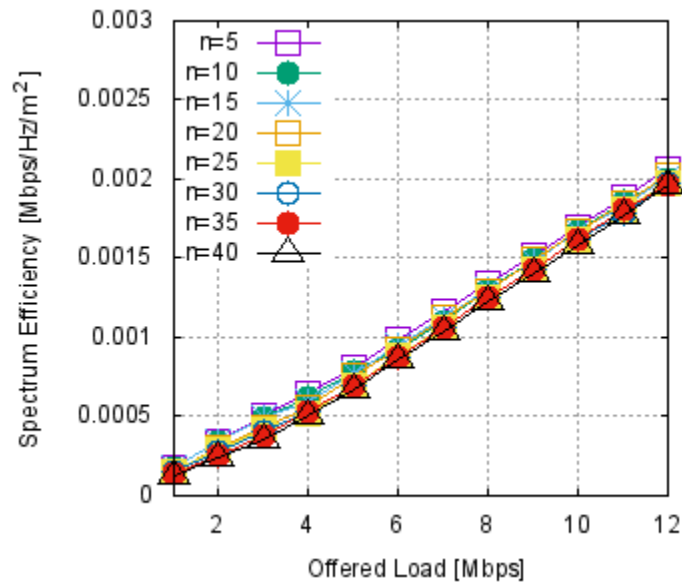


Fig. 5.26: Average area spectrum efficiency with OBSS_PD level -82 dBm for the Study 2 parametric study.

Figure *Average area spectrum efficiency with OBSS_PD level -82 dBm for the Study 2 parametric study.* illustrates the average system area spectrum efficiency with OBSS_PD level -82 dBm.

The average area spectrum efficiency with OBSS_PD level -62 dBm as offered load per BSS is increased is shown below. A separate line is plotted for each value of the number of STAs (e.g., $n=5$, $n=10$, $n=15$, ..., $n=40$).

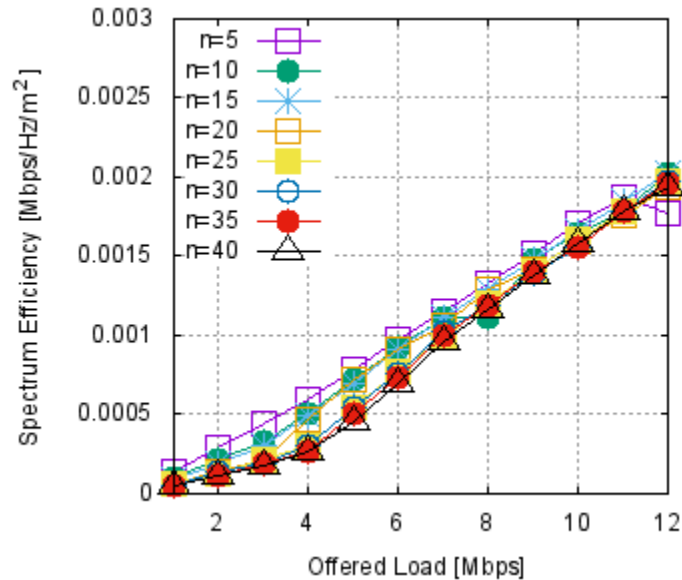


Fig. 5.27: Average area spectrum efficiency with OBSS_PD level -62 dBm for the Study 2 parametric study.

Figure *Average area spectrum efficiency with OBSS_PD level -62 dBm for the Study 2 parametric study.* illustrates the average system area spectrum efficiency with OBSS_PD level -62 dBm.

Airtime utilization

The average airtime utilization with OBSS_PD level -82 dBm as offered load per BSS is increased is shown below. A separate line is plotted for each value of the number of STAs (e.g., $n=5$, $n=10$, $n=15$, ..., $n=40$).

Figure *Average airtime utilization with OBSS_PD level -82 dBm for the Study 2 parametric study.* illustrates the average airtime utilization with OBSS_PD level -82 dBm.

The average airtime utilization with OBSS_PD level -62 dBm as offered load per BSS is increased is shown below. A separate line is plotted for each value of the number of STAs (e.g., $n=5$, $n=10$, $n=15$, ..., $n=40$).

Figure *Average airtime utilization with OBSS_PD level -62 dBm for the Study 2 parametric study.* illustrates the average airtime utilization with OBSS_PD level -62 dBm.

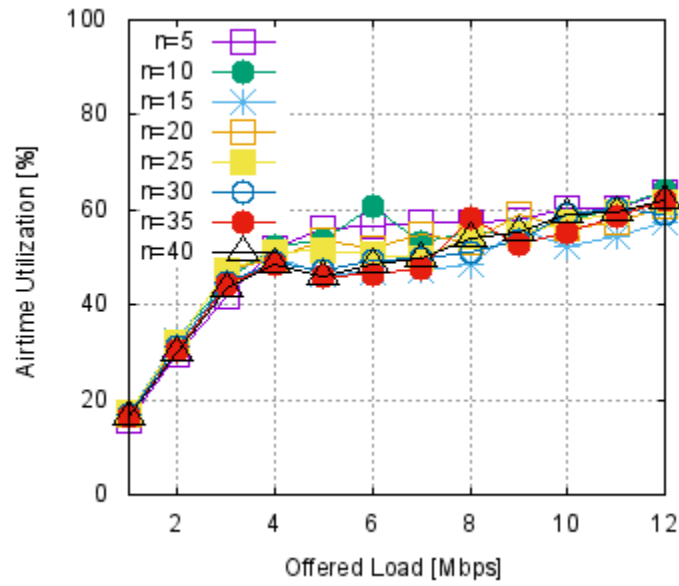


Fig. 5.28: Average airtime utilization with OBSS_PD level -82 dBm for the Study 2 parametric study.

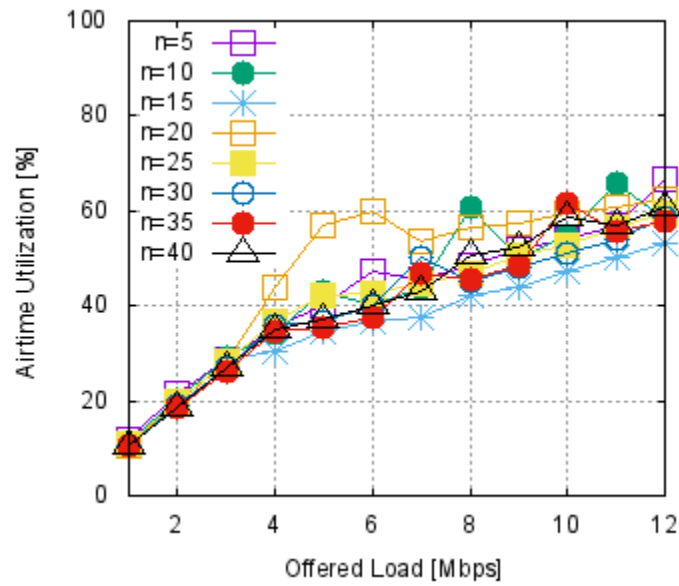


Fig. 5.29: Average airtime utilization with OBSS_PD level -62 dBm for the Study 2 parametric study.

OPEN ISSUES AND FUTURE WORK

Open Issues and Future Work in the underlying Wi-Fi model

Channel model D integration (issue #4)

Enable Time trace callback from MacLow to capture AMPDU and Block Ack events, for calibration checkpoints (issue #12)

Fix or cleanup disable wifi-he tests (issue #56)

Plot throughput results for Bianchi uplink scenario as N is varied (issue #61)

Document AP(s) in Bianchi test (issue #69)

The Bianchi validation tests would benefit from plots showing the theoretical results on the plots vs. the simulation results. (issue #73)

Block ack frame format (issue #80)

Open Issues and Future Work in the spatial reuse scenarios

Plot the CDF of latency per flow (issue #33)

Implement additional wish-list of spatial reuse scenario features and metrics (issues #10 #14)

Merge study1.sh and study2.sh into single script (issue #82)

Open Issues and Future Work in the other scenarios

Propagation models need updating, documentation, testing (issue #1)

Integrate and test LAA code (issue #5)

Some Calibration Box5 scenarios crash ns-3 (issue #43)

Rework scripts to avoid files in top-level directory ((issue #77)

BIBLIOGRAPHY

- [Sta16] Stacey, R., “Specification Framework for TGax “, IEEE document 11-15-0132-15-00ax-spec-framework, Jan. 28, 2016.
- [TGax15] Merline, S., et. al., “TGax Simulation Scenarios”, IEEE document 11-14-0980-16-00ax-simulation-scenarios, Jul. 16, 2015. IEEE 802.11-14/0980r16.