IEEE P802.11
Wireless LANs

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| HEW Evaluation Methodology |
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This document describes the simulation methodology, evaluation metrics and traffic models for assessing HEW proposals’ performance.

**Simulation Methodologies - General Concept**

Two types of simulation methodologies are defined to enable the assessment of the performance and gain of proposed HEW techniques relative to 11ac, each having its own advantages:

1. PER simulations – typically used for new PHY features for assessing point to point performance
2. System simulations – provide system-wise (multi-BSS, multi-STA) performance assessment with various degrees of detail as defined in the following three options:
	1. PHY system simulations – provide system-wise (multi-BSS) performance assessment with emphasis on PHY abstraction accuracy and very simplified MAC (e.g. transmissions are limited by CCA rules)
	2. MAC system simulations - provide system-wise (multi-BSS) performance assessment with emphasis on MAC accuracy and very simplified PHY (e.g. AWGN channel)
	3. Integrated system simulations – provide system-wise (multi-BSS) performance assessment with close-to-reality level of details accuracy by integrating both PHY and MAC

All three system simulation options have certain advantages and disadvantages:

1. Integrated system simulation:
	1. Provide comprehensive performance evaluation of PHY and MAC techniques in an environment that is close to a real-world scenario
	2. Provide deeper insight into PHY/MAC interworking:
		1. Techniques such as MU-MIMO or techniques for improving control frame delivery efficiency and reliability may require both PHY and MAC details.
		2. In some instances performance gain may only be revealed by observing the joint effects of both PHY and MAC models
		3. Enable the understanding of performance tradeoff between layers, e.g. some PHY rate enhancements may sacrifice MAC efficiency
2. PHY and MAC system simulations:
	1. Simplify some of the MAC/PHY details respectively
	2. Provide faster run time thus enabling more extensive research
	3. Speed up the project development by reducing dependency of PHY on MAC and vice versa
	4. Improve insight into the specific reason for performance gains/losses by isolating the MAC and PHY
	5. Enable accurate investigation of techniques that do not require all PHY/MAC details to be simulated

All system simulations options are used over the same simulation scenarios as defined in [10][11].

**System Simulation – High Level Description**

A system simulation is comprised of multiple drops and multiple transmission events.

A drop is defined as a specific set of AP and STA locations within a topography. Different drops have different STA locations and possibly different AP locations as defined by the simulation scenario document [11] but the topography of the environment remains unchanged.

During a transmission event a set of transmissions occurs across multiple BSS. Multiple transmission events with typical aggregate duration 1-10[sec] beyond a warm-up time are required to assess the performance of a given configuration of APs and STAs. Each BSS may have different start time, duration and end time for its transmission event but time alignment (start, duration, end) of transmission events across different BSSs in the system is a possible outcome of a proposed MAC protocol.

A’warm-up’ period may be used to allow for some parameters to converge. For example:

1. MCS selection - if the MCS adaptation algorithm requires decisions based on past performance then the warm-up period may be used for initializing the algorithm.
2. Offered load - if all flows start exactly at T0, then the offered load goes from 0 to X instantaneously, and a high number of collisions will occur when there is a large number of STAs in the scenario. It will take a warm-up time for the system to recover to a stable operating condition.
	1. The backoff mechanism will effectively reduce the total offered load of the system by increasing the CW at each competing STA and thereby reducing its offered load, until the system total offered load is at Y < X

General simulation structure:

For drop=1:N {

Drop APs and STAs according to the description in [11]

Determine the channel for every link using distance-based PL, shadowing, wall/floor loss, and multipath model.

Associate STAs with APs according to the description in [11]

For transmission event=1:M {

* + Note – one can count time, ensuring that enough time has passed to see M transmission events
	+ Note – the transmission event duration may not be the same in each BSS
	+ Generate traffic at chosen nodes. Nodes chosen in compliance with
		- CCA rules and various other EDCA parameters
		- Channel access ordering rules (round robin, proportional fair, distributed access)
	+ Generate packets consistent with a link adaptation algorithm
		- SU OL, SU BF, MU
		- MCS selection
	+ Perform transmissions
	+ Determine packet success or no
	+ Collect metrics.

}

}

**PER Simulation Description**

PHY PER simulations are used to verify point to point performance or aspects that are suitable for this type of simulation, such as new PHY features and preamble performance.

PHY impairments such as PA non-linearity, phase noise, synchronization error, channel estimation error and non-linear receivers are more readily incorporated into PER simulations and simulations that vary these parameters may be needed to test proposals if it is postulated that the techniques within those proposals are adversely affected by these impairments [6][9].

Other impairments such as the impact of OBSS interference or inter-symbol interference should also be verified by PER simulations by explicitly adding interfering packets to the simulation.

**PHY System Simulation Detailed Description**

The emphasis here is on accurate modeling of the PHY using PHY abstraction (see description in Appendix I) with focus on DATA packets.

Only the very basic MAC is simulated. This is captured in the following description of a PHY system simulation using the approach taken in [17]:

1. Drop AP’s and STA’s according to scenario (random and/or deterministic placement)
	1. Ensure that every STA <-> associated AP link can sustain MCS0 (or another predetermined MCS) in both directions. If not, re-drop STA.
	2. Channel for every link in network determined by distance-based path loss, shadowing, wall/floor loss, and multipath model
		1. Independent shadowing for every TX-RX link
		2. Deterministic values for wall & floor loss
2. Once drop has been made, for link between every pair of devices in the building have:
	1. Path loss value, with path loss value accounting for shadowing and penetration losses
	2. Multipath channel
3. TX event: determine set of active TX nodes and RX SINR based on that set
	1. Initialize visited BSS set as empty.
	2. Randomly select an un-visited BSS
		1. Identify potential TX/RX pair in selected BSS: Randomly determine downlink/uplink according to downlink probability, and randomly select one of STA’s in selected BSS
		2. Check interference level from already activated TX’s at potential TX device
			1. Sum power in linear domain across interferers and tones, and average (in linear domain) across RX antennas to get aggregate interference
			2. If interference <= threshold, activate link and add potential TX to the set of already activated TX’s
			3. If interference > threshold, do not activate.
	3. Continue above until every BSS has been tried once.
	4. Once complete, the set of active TX nodes in the current TX event has been determined.
4. For each TX event, visit BSS’s in a random order -> thereby leading to possibly different active TX set for each TX event
5. For a single drop, run many TX events and compute a per-flow throughput
6. Flow is either uplink from a STA or downlink to a STA. Total # of flows = 2 \* # STA’s
7. Perform above across many drops to get averaging across spatial distribution

An implicit assumption is made that transmissions in OBSS are time synchronized since devices hear the preamble and defer for the duration of a packet.

**Integrated System Simulation Detailed Description**

Integrated system simulation is a discrete-event simulation, which accurately models the behaviors of both PHY and MAC as a discrete sequence of events in time. Each event occurs at a particular instant in time and marks a change of state in the system. Between consecutive events, no change in the system is assumed to occur; thus the simulation can directly jump in time from one event to the next, as shown in Fig. 1.



Fig. 1 clock advancement in an event-driven simulator

The feature set of integrated system simulation includes a minimal feature list and a nice-to-have feature list, as shown Table 1.

Table 1: Feature list of integrated system simulation

|  |  |
| --- | --- |
|  | Full feature list |
| Minimum features | Nice-to-have Features |
| MAC | CCA | Multiple channels |
| Control frame (RTS/CTS/ACK/Block ACK) | Control frame (CTS2self) |
| EDCA | Management frame |
| Aggregation (A-MPDU in 11ac) | … |
| Link Adaption |  |
| Transmission mode (SU-OL, Beamforming,…) selection |  |
| PHY | Beamforming vector | MU-MIMO |
| MMSE | … |
| Effective SINR Mapping and PER prediction |  |
| Energy detection |  |

MAC process should model the features of EDCA, CCA, aggregation, control frame (RTS/CTS/ACK) transmission and reception, link adaptation and sending the receiving result to statistics collection block, as illustrated in the figure 2.



Figure 2 Detailed modelling of MAC

Notes: The feedback delay of channel state information in link adaptation should be considered.

PHY process includes abstraction of sending packets from MAC to channel, receive packets from channel and notify MAC. The following features should be detailed modeled, including beamforming vector, SINR calculation based on receiver algorithm, effective SINR mapping, PER prediction, energy detection, etc, as illustrated in figure 3.



Figure 3 Detailed modelling of PHY

The simulation procedure follows the following steps:

**Step 1: initialization**

* Drop APs and STAs according to description in [11], and initialise the internal state of each node device.
* Determine channel model for each AP and STA according to the description in [11].
* Associate STAs with APs according to description in [11].
* Create an event list as the main event scheduler of the simulator.

Notes: The location of each STA remains unchanged during a drop. Additionally, the STA is assumed to remain attached to the same AP for the duration of the drop.

**Step 2: event creation and processes**

There are three types of events defined, including traffic generation event, MAC event, and PHY event. These events are inserted into the event list, and trigger subsequent MAC/PHY processes based on their particular time instant.

* Traffic generation event: is created by upper layer at the time instant of packet generation according to the traffic model. It triggers the packet generation process to generate a packet.

Note: the packet can include only the information of time instant and size, instead of actual bit stream.

* MAC event: is created by either upper layer at a transmitter or PHY layer at receiver. MAC events created by upper layer trigger the MAC process at the transmitter for the packet in MAC layer. MAC events created by PHY layer determine whether the packet is correctly received or not based on the PER predicted in PHY and trigger MAC process at the receiver when the packet is correctly received.
* PHY event: is created by MAC layer at a transmitter when the packet in MAC layer is ready for transmission. It triggers a PHY process at a receiver to predict PER for the packet.

Step 2 includes the following processes:

* packet generation process
	+ For each traffic generation event, generate a packet including packet time instant and packet size
	+ Create a MAC event when the packet is passed from upper layer to MAC layer
	+ Create (next) traffic generation event according to each AP/STA’s traffic models

Notes: Start times for each traffic type for each STA should be randomized as specified in the traffic model being simulated.

MAC process at transmitter, if the MAC event is from upper layer:

* + Check CCA from energy detection in PHY and NAV in MAC
	+ Carry out EDCA with CSMA/CA procedure
		- Count down backoff timer
		- Send RTS/CTS configurable by scenario/technique
	+ Select transmission mode, e.g. SU OL, SU BF, MU, choose MCS, and perform packet aggregation, then create a PHY event and insert it into the event list based on the generation time of PHY event, and wait for PHY process
		- Packet aggregation rules specified in each simulation scenario are to be applied before transmission.

MAC process at receiver, if the MAC event is from PHY layer:

* + Determine the event success/failure based on PER as the abstract packet delivered by PHY
	+ Send ACK/BA if packet transmission is successful
		- Notify the packet receive results to upper layer (Optional)

PHY process

* + Each AP/STA in the network performs energy detection and updates its CCA indication
	+ Each AP/STA with channel busy in the network updates its NAV
	+ TX: obtain precoding matrix, then notify RX
	+ Channel: generate instantaneous fading channel (or load from offline files)
	+ RX: calculate SINR of each tone based on receiver algorithms, e.g. MMSE, and perform PHY abstraction to obtain post SINR, and then PER
	+ Create a MAC event to trigger MAC process at receiver

Repeat step 2 with sufficient simulation time to collect statistics.

**Step 3: Statistics collection**

Collection the statistics according to the performance metrics defined in [x]

Note: in order to obtain reliable results, sufficient numbers of drops are simulated to ensure convergence.

Following is a more detailed description:

For drop=1:N

{

Step1:

{

Drop APs and STAs according to description in [11];

Associate STAs with APs according to description in [11];

Create event list for the scheduler of simulator;

Initialize the traffic generation event for each AP/STA;

 }

Step2:

While simulation time is less than the end time

{

While traffic generation event occurs

{

Generate a packet of the size according to traffic model;

Create MAC event when the packet is passed to MAC;

Create the next traffic generation event at the time instant according to traffic model;

}

While MAC event occurs

{

If MAC event is from upper layer

{

If the CCA indicates idle and NAV is not set

{

EDCA with CSMA/CA procedure

{

Count down backoff timer;

}

Select transmission mode, e.g. SU OL, SU BF, MU;

Choose MCS;

Packet aggregation;

Create PHY events, and wait for PHY process;

}

}

If MAC event is from PHY layer

{

Determine the packet transmission success/failure based on PER;

If packet transmission is successful

{

Notify the packet receive status to upper layer (optional);

Send ACK;

 }

}

}

While PHY event occurs

{

Each AP/STA in the network performs energy detection and updates its CCA indication;

Each AP/STA with channel busy in the network updates its NAV;

TX: obtain precoding matrix, then notify RX;

Channel: generate instantaneous fading channel (or load from offline files);

RX: calculate SINR of each tone based on receiver algorithms, perform PHY abstraction to obtain post SINR and get PER;

Create a MAC event to notify PER to MAC, and wait for MAC process;

}

}

Step3:

 Collect statistics.

}

**MAC System Simulation Description**

MAC system simulation is an integrated system simulation stripped out of the details of PHY modelling, e.g. a SISO configuration with AWGN - path loss and penetration loss should be modeled according to the scenario-specific definition.

**Simulation Methodology Choice**

Proponents of different techniques should provide justification for their proposed simulation methodology used to justify the technique’s gains. Proponents should also provide a comparison to performance with baseline parameters, e.g. .11ac.

Examples:

* PHY PER simulation:
	1. New PHY – a PER simulation is typically sufficient in order to decide the number of pilots, interleaver parameters and other parameters.
	2. Preamble performance
	3. Implementation losses of current and new PHY modes.
	4. Interference, especially if varying across the packet, impact on PER.
* PHY System simulation:
	1. Impact of number of antennas on multi-BSS performance
	2. Impact of PHY techniques in the context of multi-BSS
	3. Impact of frequency re-use in multi-BSS
	4. Impact of CCA levels on system throughput
* MAC System simulation:
	1. Impact of MAC scheduler – for example EDCA vs. RAW (as in 11ah) vs. HCCA vs. other techniques
	2. Impact of frequency re-use in multi-BSS
	3. Impact of CCA levels
* Integrated System simulation:
	1. Performance evaluation of HEW solution in the environment close to real-world
	2. Impact of crosslayer techniques affecting both PHY and MAC layers in the context of multi-BSS

Note that some techniques can be simulated using multiple simulation tools to provide better insight

**System Simulation Calibration**

Calibration of all system simulations is used to harmonize results between multiple entities and is depicted in the following flow chart.



Top box: Long-term statistics calibration

* The objective is to align the distribution of static radio characteristics.
* Static radio characteristics reflect the deployment, STA-AP association, and large-scale fading channel generation.

Mid-left box: multipath and MIMO are added

* The objective is to align distribution of accurate realistic channels (small and large scale fading) with MIMO configurations.

Mid- right box: MAC system simulator calibration.

* The objective is to align the MAC system simulator using a defined set of features

Bottom-left box: PHY system simulator

* The objective is to align the PHY system simulator.

Bottom-right box: Integrated system simulator calibration

* The objective is to align a combination of all PHY and MAC features

**Traffic Models**

Full buffer model is baseline – users always have DATA to send and receive.

A more realistic FTP traffic model may be used based on [15]. Specifc parameters are TBD.

A mix of small and large packets should be evaluated in order to test realistic assumptions on system performance.

In addition, specific traffic models for Video [16] are TBD.

**Metrics**

HEW evaluation methodology defines evaluation of spectrum efficiency improvement in both link level and system level.

Link Level Simulation

For PER simulations the typical metric is dB gain/loss in waterfall curves. The operating range to be observed is 1% to 10% PER.

System Level Simulation

For system simulations it is suggested to use the following metrics to evaluate the system performance [2]-[9], [19]-[21]:

1. Per-STA Throughout

Per-STA throughput metrics are used to measure the user experience in the area covered by one or multiple BSSs in different simulation scenario [11].

Definition – Per-STA throughput is measured at MAC SAP by the number bits (or bytes) of MAC payload successfully transmitted over the given measurement period in the full buffer simulation.

• Per-STA throughput at 5 percentile of throughput CDF curve measures the minimum throughput performance of stations at the cell edge.

• Per-STA throughput at 50 percentile of CDF curve measures the average throughput of stations in all participating BSS in the simulation.

• Per-STA throughput at 95 percentile of CDF curve measures the top performance of stations at the cell center of BSS.

Although the main target of HEW is to improve the performance at 5 and 50 percentile of throughput CDF curve, it is suggested to measure Per-STA throughput at the 5, 50, and 95 percentile points. The entire throughput CDF curve and other information such as MCS histogram may help to evaluate the overall system performance improvement [3].

Per-STA throughout for DL and UL are measured separately.

1. Per-BSS Throughput

Per-BSS throughput is used to evaluate BSS capacity in the various simulation scenarios described in [11]. This metric directly relates to the aggregated Per-STA throughputs in BSS and can be used to compare different deployment densities and heterogeneous deployments.

Definition – Per-BSS throughput is the aggregated Per-STA throughput among all the associated stations in a BSS.

Per-BSS throughout could be measured by aggregating Per-STA throughputs of all the stations in a BSS, or derived from Per-STA throughput times the number of associated stations in a BSS.

Per-BSS throughout for DL and UL are measured or calculated separately.

1. Packet Loss

The packet loss metric is used to evaluate the system robustness especially in the high density deployment scenario. This metric reflects an aspect of system performance different from throughput and transmission latency.

Definition – The packet loss is defined as the number of MAC packet not delivered at all or not delivered in time to the receiver over the total number of offered MAC payloads.

The packet loss means that the MAC packet could not be decoded by the receiver due to the interference or low RSSI, or the MAC packet could not be delivered at the receiver in time for QoS flow due to traffic congestion.

1. Transmission Latency

The metric of transmission latency is used to measure the time delay of medium acquisition in channel access mechanism. The transmission latency is used to evaluate an aspect of MAC performance in various QoS transmissions.

Definition – The transmission latency is measured from the time that MAC receives a packet till the time that PHY starts transmitting.

The transmission latency may include the time delay of

• AIFS

• Backoff time

• Other system parameters

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**Appendix I - PHY Abstraction**

The objective of PHY abstraction is to accurately predict PER simulation results in a computationally efficient way to enable running system simulations in a timely manner.

The underlying principle is to calculate an effective average SINR (*SINReff* ) in a given OFDM symbol. This quantity then acts as a link between AWGN PER and multipath channel PER for a given coding type, block size and MCS level.

Effective SINR (*SINReff* ) is typically calculated as follows

where *SINRn* is the post processing SINR at the *n*-th subcarrier, *N* is the number of subcarriers in a coded block and Φ is a mapping function.

Several mapping functions can be used such as Constrained Capacity, EESM, MMIB, RBIR, etc. [12]

A general description is as follows:

* + Start from an agreed upon per-MCS required SNR in AWGN assuming 1000bytes SISO 10% PER point.
	+ With one receive antenna:
		1. Compute SINR per tone – the ‘S’ term is a function of the Tx power and channel. The ‘I’ term is due to OBSS, intra-BSS interference or MU-MIMO related interference. Note that ‘I’ could vary during a packet due to shorter interfering packet than the desired packet or start of new interfering packet midway through the desired packet.
		2. Transform to MCS using one of several methods:
	+ Constraint capacity - calculate the per-tone capacity log2(1+SINR), this could be constrained to 256QAM capacity, and average across all data tones used for transmission to arrive at the average capacity. From the average capacity derive the average SINR per tone and transform back to MCS using the AWGN MCS table.
	+ MMIB - calculate the average per-bit capacity as described in [13]
	+ RBIR - calculate the symbol information as described in [14].
* With multiple receive antennas:
	+ 1. SINR should reflect the receive combining output from all antennas and the combining method should be indicated
		2. For MIMO reception, a linear MMSE receiver can be assumed (see description in section 4.4.4 of [12]) to be applied to the MIMO channel to generate an SINR per spatial stream.