Komondor: an Event-Based Wireless Network Simulator for Next-Generation IEEE 802.11ax WLANs

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Abstract

Komondor is a wireless network simulator that includes novel mechanisms for next-generation WLANs, such as Dynamic Channel Bonding or enhanced Spatial Reuse. One of Komondor's main purposes is to emulate the behavior of IEEE 802.11ax-2019 networks, which main challenge is spectral efficiency in dense deployments. Furthermore, due to the growing popularity of autonomous systems and the tendency of WLANs to use learning, Komondor is intended to include intelligent agents that make decisions that allow enhancing the network performance.

In this document we provide an overview of the Komondor simulator, making insight on its main features, its operational mode and its development stages. Komondor has been conceived as an open source tool that contributes to the ongoing research in wireless networks. For that, all the contents are published at the following public repository: `https://github.com/wn-upf/Komondor`. Any interested researcher is invited to collaborate.

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1 Introduction

Komondor [1] is an event-based simulator based on COST [2], a CompC++ library that allows generating discrete event simulations.[1] Komondor is mostly intended to reproduce the novel techniques included in the IEEE 802.11ax-2019 amendment [3], which is called to become a benchmark in next-generation wireless networks. Furthermore, due to the increasing popularity of learning-based approaches in WLANs, our simulator is being built to allow the inclusion of intelligent agents that make decisions in simulation time. The decision of building a new wireless networks simulator is based on *i*) the lack of 11ax-oriented simulators that include novel techniques, *ii*) the need of generating a tool able to simulate intelligent agents behavior and, *iii*) the difficulty in extending other existing solutions (e.g., ns-3) towards our abovementioned main goals.

Komondor is a long-term and iterative project which goals are mostly focuses in providing a reliable and accurate IEEE 802.11ax simulator. In this document we present its version v1.0, which includes the core functionalities to provide a basic operation.

1.1 Next-Generation WLANs

The increasing popularity of IEEE 802.11 WLANs has led to new strict requirements in terms of data rate and users capacity. Such situation has brought the wireless communications community to introduce novel approaches. In particular, the 11ax amendment is being developed to improve spectrum efficiency in high density scenarios. To accomplish that, it introduces the concept of High-Efficiency (HE) WLANs, which incorporates novel techniques such as OFDMA, Dynamic Channel Bonding, Beamforming and Multi-User Multiple-Input Multiple-Output (MU-MIMO) [4]. Such advanced mechanisms drastically change the current operation of WLANs and have not been previously implemented with detail in other network simulators.

In addition to the novel HE techniques, wireless networks are evolving towards autonomous management, which in many cases is achieved through Artificial Intelligence (AI). Its utilization is expected to be key in next-generation complex systems, since it allows solving (or at least approximating) computational-intensive problems. In particular, online learning has been previously applied in well-known problems such as Transmit Power Control (TPC), Carrier Sense Threshold (CST) adjustment and channel allocation [5, 6, 7, 8]. Since most of the literature that applies learning into wireless networks is theoretical in nature, there is a strong need of tools that allow implementing learning algorithms in a realistic simulation environment.

1.2 Komondor Main Features

Komondor aims to realistically capture the operation of wireless networks. Henceforth, it reproduces actual transmissions on a per-packet basis. For that, nodes properties (e.g., location, transmit power, CCA threshold) are taken into account during data exchange procedures. The initial version of the Komondor simulator includes the following functionalities:

- **Flexible input files processing with error control**: network capabilities can be introduced into the simulator in a very flexible manner. Moreover, an input checker is provided in order to identify the most prominent errors in the input provided by the user.
- **IEEE 802.11ax WLANs features implemented in version v1.0**:
  - **Distributed Coordination Function (DCF)**: the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) captures the basic Wi-Fi operation for accessing the channel. Moreover, Contention Window (CW) adaptation is considered.
  - **Channel Bonding (CB)**: several channel ranges can be selected during transmissions in order to maximize the spectrum efficiency.
  - **Packet aggregation**: several MPDUs can be aggregated into the same PPDU in order to reduce the generated communication overheads.

[1] COST main website: http://www.ita.cs.rpi.edu/cost.html

- **Dynamic Modulation Coding Scheme (MCS)**: the MCS is negotiated between any transmitter-receiver pair according to the Signal-to-Interference-and-Noise Ratio (SINR).
  - **Ready-to-Send/Clear-to-Send (RTS/CTS) and Network Allocation Vector (NAV)**: nodes exchange packets before transmitting in order to allocate the channel and prevent collisions.

- **Statistics**: different metrics of interest are gathered and properly presented.

Future development stages are considered to include other features such as OFDMA, MU-MIMO transmissions, beamforming, or dynamic transmit power and CST adjustment.

1.3 COST

In order to provide a deeper understanding of Komondor, it is important to comprehend the COST library, which allows building interactions between components (e.g., wireless nodes). Such interaction is achieved through synchronous and asynchronous events. While the former are messages explicitly exchanged between components through input/output ports, the later are based on timers.

In practice, components perform a set of operations until a significant event occurs. For instance, a node that is decreasing its backoff (i.e., current operation) may freeze it when an overlapping node occupies the channel (i.e., an event). Moreover, the node may start a transmission when the backoff timer is over (i.e., a trigger). Figure 1 shows the schematic of a COST component, which is characterized by its inports and outports, and a set of timers.

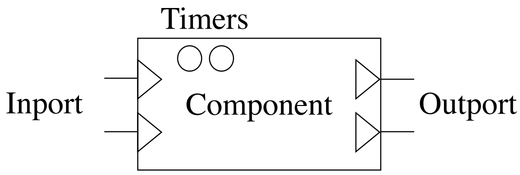


Figure 1: COST component. While inports and outports allow to directly communicate with other components, timers trigger events specific to the component.

1.4 Contributions

In this document we describe the main features of the Komondor simulator and system model considerations, as well as some basic guidelines to run it. The main contributions done in this document are listed below:

- We provide an overview of the first version of the Komondor simulator.
- We describe the implementation done for each of the included functionalities, as well as the main considerations done.
- We provide a set of validations that ensure the proper operation of the presented simulator.
- We provide a tutorial to allow an easy installation and execution of the simulator. Moreover, some implementation details are granted in case the reader is interested in extending the simulator.

Note, as well, that detailed technical information regarding code development is out of the scope of this document. Please, refer to the GitHub repository for more details on code implementation.

1.5 Document Structure

This documents is structured as follows: Section 2 describes the main design principles of Komondor. Then, Section 3 defines the implementation of IEEE 802.11 functionalities considered so far, which are validated in Section 4. A tutorial and some development notes are provided in Section 5. Finally, some remarks are given in Section 6.

2 Komondor Design Principles

One of the main tasks regarding the implementation of Komondor relies on defining its design principles, which lay the foundations of the simulator. In this Section we describe the models defined for simulating the different communication aspects that a wireless device is intended to implement.

2.1 Channel Modeling

Channel modeling characterizes the signal propagation effects between the transmitter and the receiver. In order to be flexible and allowing to simulate different scenarios and casuistic, we define a set of path-loss and co-channel interference models, which are described next.

2.1.1 Path-loss Models

In order to provide the most representative wireless environments, we implemented the following set of path-loss models, which can be further extended by any developer:

- Free Space Path Loss (FSPL): a free-space model is considered, which captures direct line-of-sight and ignores shadowing effects. The experienced loss of power during a transmission that assumes this model is given by:

$$\text{FSPL} = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right) - G_t - G_r,$$

  where d is the distance between the transmitter and the receiver, f is the frequency used in GHz, c is the light speed in m/s, and G_t and G_r are the gains in dB at the transmitter and the receiver, respectively.

- Okumura-Hata model [9]: this well-known model was conceived for predicting the path-loss of cellular transmissions in outside urban and rural environments. Since our main concern is related to dense urban areas, let the loss, L_U, be given by:

$$\begin{aligned} L_U = &69.55 + 22.16\log_{10}(f) - 13.82\log_{10}(h_B) + (44.9 - 6.55\log_{10}(h_B))\log_{10}(d) - \\ &3.2\log_{10}(11.7554 h_M)^2 - 4.97, \end{aligned}$$

  where f is the center frequency in MHz, h_B is the height of the transmitter antenna, d is the distance between the transmitter and the receiver in meters, and h_M is the height of the receiver's antenna.

- Indoor model: this model represents a simple indoor scenario, which is useful to simulate typical scenarios such as flats, schools or restaurants. According to this model, the loss, L_{indoor}, experienced during a transmission is:

$$L_{indoor} = \text{PL}_f + 10\alpha\log_{10}(d) + h_s + \left(\frac{d}{f_w}\right)h_o,$$

  where PL_f is the path-loss factor, α is a constant that depends on the propagation model, d is the distance in meters between the transmitter and the receiver, h_s is the shadowing factor, f_w is the frequency of walls, and h_o is the obstacles factor.

  Furthermore, a variation of this path-loss model is provided, in order to introduce random variables that determine the shadowing and obstacles effects in the power losses.

- Residential path-loss model IEEE 802.11ax: such model is included in the 11ax amendment, and captures the path-loss effects of a typical apartments building. The loss, $L_{indoor-ax}$, experienced during a transmission is given by:

$$\begin{aligned} L_{indoor-ax} = &40.05 + 20\log_{10}\left(\frac{f_c}{2.4}\right) + 20\log_{10}(\min(d,5)) + (d>5)35\log_{10}\left(\frac{d}{5}\right) + \\ &18.3F^{\frac{F+2}{F+1}-0.46} + 5W, \end{aligned}$$

  where f_c is the frequency in GHz, d is the distance between the transmitter and the receiver, F is the number of floors traversed, and W is number of walls traversed in the x-direction plus the number of walls traversed in the y-direction

2.1.2 Adjacent Channel Interference Models

In addition to the introduced path-loss types, it is important to take into account the Adjacent Channel Interference (ACI), which conditions the interaction between devices. The fact of using non-overlapping channels entails more aggressive interactions given that devices in other channels also contribute to the sensed interference in a given receiver. An example of channels overlapping is shown in Figure 2.

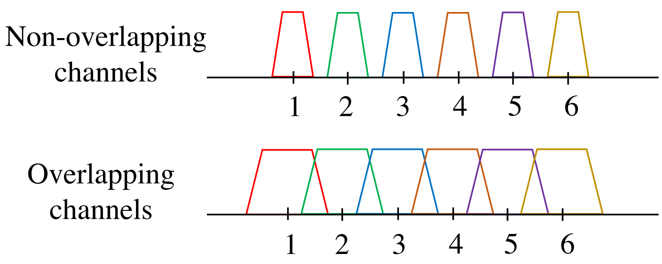


Figure 2: Channel models with and without ACI

In particular, Komondor includes the following ACI models:

- **No interference**: no power is leaked to adjacent channels.
- **Total interference**: power from other channels is leaked, so that a 20 dB decrease is noticed for each channel distance. For instance, the power that channel 1 leaks into channel 3 is the actual power in channel 1 minus 40 dBr.
- **Limited interference**: in this case, only immediate adjacent channels leak power to the target one, so that a 20 dB decrease is noticed from consecutive channels.

A critical assumption done in Komondor is that the incoming power in a given receiver is assumed to be the same during the entire transmission. This relaxation allows us to easily determine whenever the channel of interest is busy or not. A direct implication of it affects to path-loss models used, as well as some of them assume random variations of the medium, preventing to obtain the same result with different power received calculations (so far, power received is added and subtracted when the node accesses and leaves the channel, respectively). Thus, for each node, Komondor stores the incoming power of a given transmission when it begins and subtracts the power when it is over.

2.2 Traffic Modeling

Traffic modeling refers to the capacity of generating data in higher transmission layers. So far, Komondor only considers downlink traffic, so that data transmissions are initiated by APs. Regarding traffic generation, we have considered three different models:

- **Full buffer**: transmitters are in a permanent saturation regime, so that they always have packets to be sent.
- **Poisson**: packets are generated according to a Poisson distribution process, so that the average time between packets is determined by the packet generation rate λ, and which is given by $\Delta_\text{p} = \frac{1}{\lambda}$.
- **Deterministic**: packets are generated at fixed time intervals given by the packet generation rate, $\Delta_\text{d} = 1/\lambda$.

Figure 3 illustrates the aforementioned traffic models.

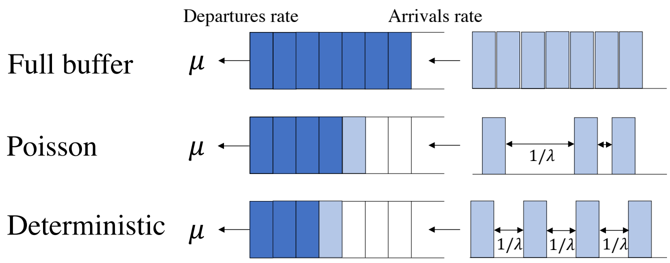


Figure 3: Traffic models used in Komondor

MCS index	SINR interval (dBm)	Modulation type	Coding rate	Data rate (Mbps)			
				20 MHz	40 MHz	80 MHz	160 MHz
0	[-82, -79)	BPSK	1/2	4	8	17	34
1	[-79, -77)	QPSK	1/2	16	33	68	136
2	[-77, -74)	QPSK	3/4	24	49	102	204
3	[-74, -70)	16-QAM	1/2	33	65	136	272
4	[-70, -66)	16-QAM	3/4	49	98	204	408
5	[-66, -65)	64-QAM	2/3	65	130	272	544
6	[-65, -64)	64-QAM	3/4	73	146	306	613
7	[-64, -59)	64-QAM	5/6	81	163	340	681
8	[-59, -57)	256-QAM	3/4	98	195	408	817
9	[-57, -54)	256-QAM	5/6	108	217	453	907
10	[-54, -52)	1024-QAM	3/4	122	244	510	1021
11	$\geq$ 52	1024-QAM	5/6	135	271	567	1143

Table 1: Data rates granted per MCS in IEEE 802.11ax. Guard Intervals (GI) of 1600 ns are only considered.

2.3 Link Modeling

In order to determine the data rate to be used during a given transmission, the MCS table defined in the IEEE 802.11ax is considered. Komondor assumes that the MCS used between a pair of devices is determined by the SINR at the receiver, so that the maximum allowable MCS is used. The required SINR that corresponds to each MCS is defined in Table 1, as well as the granted data rate for each channel width.

So far, link adaptation is not considered[2]. Instead, the MCS to be used between each transmitter-receiver pair is negotiated at the beginning of the first transmission, which remains static throughout all the simulation. In practice, the highest possible modulation is computed between each transmitter-receiver pair according to the SINR at the receiver.

Finally, regarding the transmission time for sending a packet, it is computed as a function of the data rate and the size of the packet to be transmitted. Packet lengths are defined according to the IEEE 802.11ax specification, which is further described in Section 4.1.

2.4 Collisions Modeling

Collisions are critical to be implemented because they determine the actual performance in a given network, thus allowing to capture situations that may occur in real environments. In particular, packet losses mostly occur because two nodes transmit at the same time (their backoff reaches 0 simultaneously) hidden-node effects or link asymmetries. An example of a hidden-node collision is shown in Figure 4, in which nodes A and C transmit simultaneously to B because they do not sense the other's transmission. The resulting interference may lead into a collision and provoke that none of the packets can be properly decoded.

In Komondor, a packet loss is considered when the ACK timeout expires at a given transmitter. However, it is critical to identify what caused such loss, which may allow to further analyze the issue. In particular, Komondor is able to categorize packet losses as follows:

[2] Future work contemplates the inclusion of Minstrel as a rate adaptation scheme.

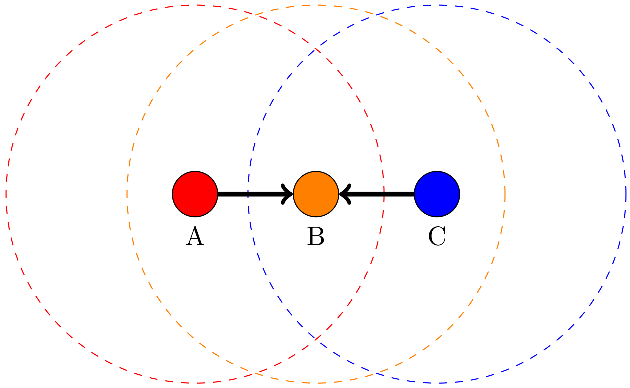


Figure 4: Hidden-node cause of collision

- **PACKET_LOST_DESTINATION_TX**: packet is discarded because the destination was already transmitting when the packet transmission was attempted. In this case we know that the transmitter could not listen to the receiver at the moment of starting a transmission.
- **PACKET_LOST_LOW_SIGNAL**: the packet cannot be decoded because the signal strength is not enough (i.e., it is less than the CCA).
- **PACKET_LOST_INTERFERENCE**: packet is lost due to interference sensed at the receiver, which does not accomplish the capture effect condition.
- **PACKET_LOST_PURE_COLLISION**: packet is lost because two nodes transmit to the same destination, so that both signal strengths are high enough to be decoded at the receiver (the situation shown in Figure 4).
- **PACKET_LOST_LOW_SIGNAL_AND_RX**: the destination is already receiving data when a new data transmission starts. However, the newest signal strength is not high enough to be decoded in normal conditions. This event comprises the abovementioned PACKET_LOST_DESTINATION_TX and PACKET_LOST_LOW_SIGNAL causes.
- **PACKET_LOST_RX_IN_NAV**: packet is lost because the target node is in a NAV period (it previously decoded an RTS/CTS sequence).
- **PACKET_LOST_BO_COLLISION**: the packet is lost because a backoff collision occurred (i.e., two or more interfering devices ended their backoff simultaneously), provided that the interfering signal is strong enough to cause a collision.

3 IEEE 802.11 Features

In this Section we provide an overview of the main MAC layer features included in Komondor, so that their practical implementation can be further understood.

3.1 Channel Access

When a wireless device has a packet to be sent, it employs DCF to access the medium, which makes use of CSMA/CA and BEB. With that, transmissions are carried out if the target channel has been empty for a given Backoff (BO) time, which is computed according to a dynamic CW. A channel is considered to be empty if the interference in it is lower than a Clear Channel Assessment (CCA) threshold. Furthermore, a packet transmission is successful whenever the receiver SINR is equal or higher than the Capture Effect (CE) threshold, which allows defining the rate at which packet losses occur, regardless on the Modulation Coding Scheme used.

3.1.1 Distributed Coordination Function

As previously mentioned, the CSMA/CA operation is based on the DCF, which orchestrates channel access in a distributed manner. Roughly, transmitters (e.g., devices that have data to be transmitted) choose a random BO value, which is decremented only if the channel is sensed as idle due to the CCA condition. Otherwise, the BO is paused and the transmission is delayed. Figure 5 shows an example of the DCF operation in which three nodes listen to each other in the same wireless scenario. As it is shown, STA2 wins the channel access because its initial BO timer is the lowest one. During the packet transmission, STA1 listens the channel busy and stops its BO operation. Once data transmission is finished and the channel has been idle for a DIFS interval, the BO procedure is activated in all the devices that have a packet to be transmitted and sense the channel idle.

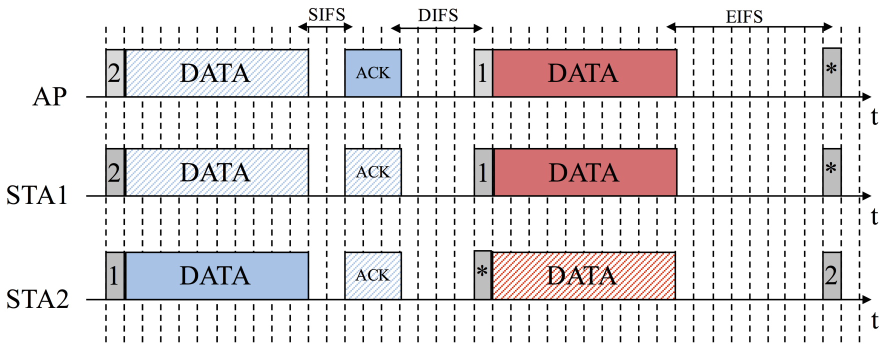


Figure 5: Example of the DCF procedure

Regarding BEB, it determines the process of generating the BO, which depends on the Contention Window (CW). The CW is dynamically adapted on a per-packet basis, so that the CW increases or decreases according to successful/failed transmissions. Given a minimum and a maximum boundaries for CW ($\mathrm{CW}_{\mathrm{min}}$ and $\mathrm{CW}_{\mathrm{max}}$, respectively), the reset operation is performed when a successful transmission is carried out. In such situation, the CW is set to $\mathrm{CW}_{\mathrm{min}}$. Otherwise, when packet losses occur, the CW is increased without exceeding $\mathrm{CW}_{\mathrm{max}}$. To do so, a counter (namely $\mathrm{CW}_{\mathrm{count}}$) is maintained and increased one unit each time a packet loss occurs. Then, the CW is computed as $\mathrm{CW} = \mathrm{CW}_{\mathrm{min}} \times 2^{\mathrm{CW}_{\mathrm{count}}}$.

Furthermore, Komondor provides two different ways of computing the BO value as a function of the CW:

- **Uniform**: the generated BO is a number between 0 and $\mathrm{CW}-1$, and all the values have the same probability.
- **Exponential**: instead of using an uniform distribution, we use an exponential one, so that the generated BO is given by the mean CW value ($\frac{\mathrm{CW}-1}{2}$).

An important consideration with respect to the discrete BO implementation considered in Komondor, is that devices are synchronized, which allows reproducing collisions by BO that depend on the congestion window and the number of coexisting nodes.

3.1.2 Capture Effect

In order to successfully decode the signal received, a receiver must perceive that the desired signal strength is bigger than a CE threshold, so that the received data can be distinguished among noise and interference present in the channel. Komondor considers an *stronger-first* interference pattern for the data exchange process. Henceforth, a data packet is properly decoded only if posterior transmissions do not generate high enough interference to discard it. Note that a dominant data transmission is not going be considered at a given receiver that is already receiving any type of data from another node. In such case, both transmissions are considered to be lost. The stronger-first CE principle is shown in Figure 6.

3.2 RTS/CTS and NAV Allocation

The RTS/CTS mechanism is implemented in order to minimize the collisions by hidden node. Through RTS/CTS, transmitting nodes attempt to block the channel for the duration of their transmissions. For that, they send RTS packets and wait for confirmation about the clearness of

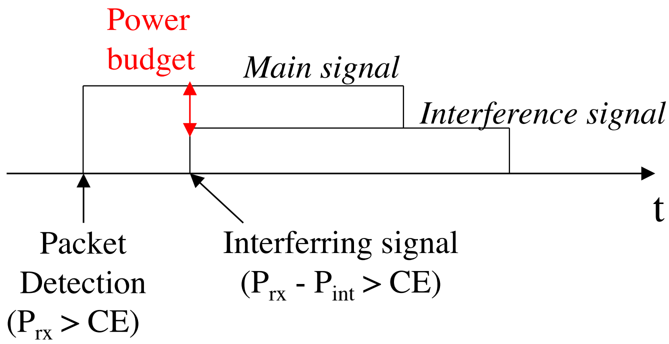


Figure 6: Stronger-First Capture Effect example

the channel from the receivers' point of view. Through such packet exchange, overlapping nodes must set a virtual carrier sensing during the transmission duration, which allows reducing the collisions by hidden node. The RTS/CTS operation is exemplified in Figure 7. The scenario shown in Figure 4 is considered, so that the AP is the middle and both STAs do not sense each other.

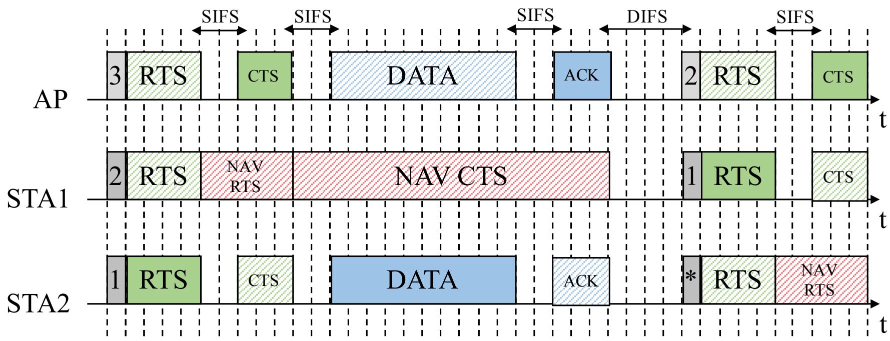


Figure 7: Example of RTS/CTS implementation. The transmitter (STA2) sends an RTS packet before starting a transmission. The receiver (AP) answers with a CTS as it senses the channel free. The other coexisting devices (STA1) that listen either the RTS and/or the CTS, set their NAV accordingly.

3.3 Channel Bonding

Dynamic channel bonding (DCB) is one of the most promising techniques to enhance spectral efficiency in IEEE 802.11ax WLANs, since it aims to make the most of the medium by transmitting data over several contiguous basic channels. For that, different DCB policies are implemented in Komondor, which can be interchangeably applied by the simulated WLANs. To perform DCB, one may explicitly define the available range of basic channels for each WLAN. Then, the following policies can be applied:

- **Only Primary (OP)**: the legacy operation is performed, so that only the primary channel is attempted to be accessed. This policy is also known as single-channel.
- **Static Channel Bonding (SCB)**: carrier sensing is performed at the primary channel. However, when attempting to transmit, all the channels within the CB range must be clear. Otherwise, a new backoff is computed.
- **Always-max (AM)**:[3] picks the widest possible channel found free for transmitting. Note that, in order to include secondary basic channels for transmitting, a WLAN must listen

[3] Some papers in the literature use the terms DCB and AM indistinctly. In this document we notate AM as an special case of DCB.

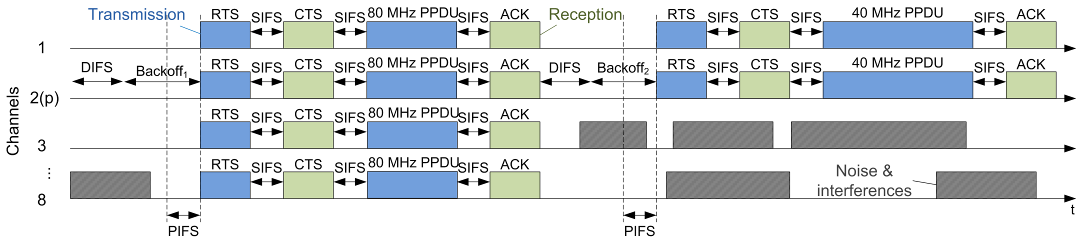


Figure 8: CSMA/CA temporal evolution of a node operating under AM and the IEEE 802.11ax channelization scheme.

them free during at least a PIFS period before the backoff counter terminates as shown in Figure 8.

- **Probabilistic uniform (PU)**: picks with same probability any of the possible channels found free inside the allocated channel.

For the sake of illustration, let us consider the example shown in Figure 8, where the evolution of a node implementing AM is presented. Regarding the rest of DCB policies, *i*) OP would just pick channel 2 after both backoff terminations, *ii*) SCB would only transmit after the first backoff termination as part of the rest of basic channels is busy after the second one, and *iii*) PU would transmit on channels $\{2\}, \{1,2\}, \{1,2,3,4\}$ or $\{1,2,...,8\}$ with same probability $(1/4)$ at the first backoff termination, and on channels $\{2\}$ or $\{1,2\}$ with probability $1/2$ at the end of the second one. An schematic flowchart of the DCB policy operation is shown in Figure 9.

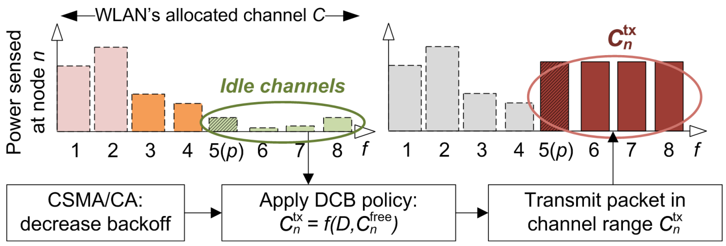


Figure 9: Flowchart of the transmission channel selection. In this example channel 5 is the primary channel and AM is applied.

3.4 Packet Aggregation

Packet aggregation aims to reduce transmission overheads such as headers, SIFS and DIFS intervals or backoff periods. For that, it concatenates N MPDUs to be sent over the same packet transmission, so that it can be acknowledged through a block ACK. Komondor allows to define the number of aggregated packets, which value remains static during the entire simulation.

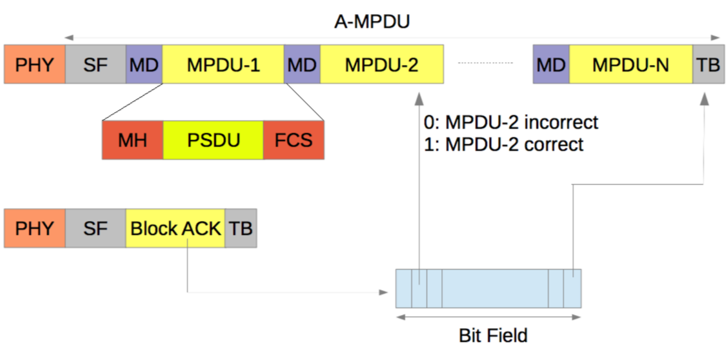


Figure 10: Example of packet aggregation in which N MPDUs are concatenated to be sent during the same packet transmission.

4 Komondor Main Features Validation through CTMN

In this Section we aim to provide a mutual validate the core operation of Komondor by using a set of key scenarios. Moreover, we a mutual validation is done by considering the Continuous Time Markov Networks (CTMNs) model [10]. To do so, we use the Spatial-Flexible Continuous Time Markov Network (SFCTMN),[4] an analytical framework based on Continuous Time Markov Networks (CTMNs). This framework is useful for describing the different phenomena that occur in WLANs scenarios when considering DCB in non-spatially-constrained deployments, i.e., where nodes are not required to be within the carrier sense range of each other.

4.1 IEEE 802.11ax Parameters

Before showing the set of Komondor validations, we introduce in Table 2 the IEEE 802.11ax parameters that we consider for simulations, and which are recommended to be kept in order to emulate 11ax's behavior.

Table 2: Parameters considered in the IEEE 802.11ax scenarios.

Parameter	Description	Value
CW_{min}	Min. contention window	16
m	Backoff stage	5
CCA	CCA threshold	-82 dBm
P_{tx}	Transmission power	15 dBm
G_{tx}	Transmitting gain	0 dB
G_{rx}	Reception gain	0 dB
L_{data}	Length of a data packet	12000 bits
L_{BACK}	Length of a block ACK	240 bits
L_{RTS}	Length of an RTS packet	160 bits
L_{CTS}	Length of a CTS packet	112 bits
n_{agg}	Num. data packets aggregated	64
CE	Capture effect threshold	20 dB
N	Background noise level	-95 dBm
T_{slot}	Slot duration	9 μs
SIFS	SIFS duration	16 μs
DIFS	DIFS duration	34 μs
PIFS	PIFS duration	25 μs
η	Packet error rate	0.1
f_c	Central frequency	5 GHz
T_{ofdm}	OFDM symbol duration	16 μs
T_{phy}	Legacy PHY header duration	20 μs
n_{ss}	SU spatial streams	1
$T_{\text{phy}}^{\text{HE}}$	HE header duration	32 μs
L_{sfF}	Length of MAC's service field	16 bits
L_{del}	Length of MAC's MPDU delimiter	32 bits
L_{mac}	Length of MAC header	272 bits
L_{tail}	Length of MAC's tail	6 bits

4.2 Basic Operation Validation

The basic operation of Komondor regarding the DCF implementation with additional features such as RTS/CTS is first validated in the scenario shown in Figure 11, which frames a single WLAN composed by an AP and two STAs. All the devices are within the same range, so that channel access is completely fair. However, in order to give priority to the AP, its CW is smaller than

[4] All of the source code of SFCTMN is open, encouraging sharing of algorithms between contributors and providing the ability for people to improve on the work of others under the GNU General Public License v3.0. The code version used in this work can be found at https://github.com/sergiobarra/SFCTMN.

the one used by STAs. The performance achieved by each device is shown in 3, where Komondor results are compared to equivalent ns-3 simulations, and to the Bianchi's analytical model [11].

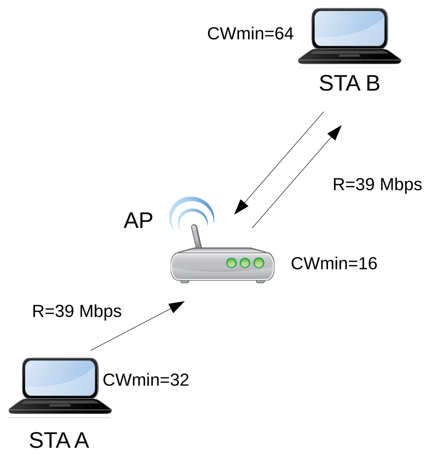


Figure 11: SCENARIO I (TEMPORARY IMAGE)

Table 3: Results for Komondor validations in Scenario I. The average throughput experienced by each device is shown for ns-3, Bianchi and CTMNs simulations.

	Komondor	ns-3	Bianchi	CTMNs
Γ_{AP}				
Γ_{STAA}				
Γ_{STAB}				

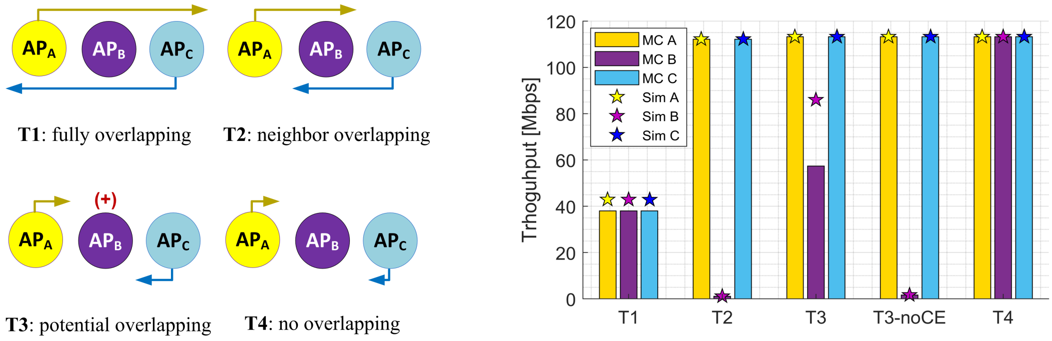
4.3 Complex Interactions Validation

Now, in order to further validate the Komondor simulator, we propose the following set of partial-overlapping scenarios, which are shown in Figure 12a:

- **Topology 1 (*T1*)**: all the nodes are able to listen each other, so that they share the channel on equal terms.
- **Topology 2 (*T2*)**: either AP_A or AP_C generate enough interference to contend AP_B's transmission.
- **Topology 3 (*T3*)**: simultaneous transmission of both AP_A and AP_C generates enough interference to make AP_B sense the channel busy.
- **Topology 4 (*T4*)**: none of the nodes' transmission is sensed by the others.

The average throughput experienced by each WLAN in each of the regions is shown in Figure 12b. Regarding topology *T1*, when APs are close enough to be inside the carrier sense range of each other in a fully-overlapping manner, the medium access is shared fairly because of the CSMA/CA mechanism. For that reason, the throughput is decreased to approximately 1/3 with respect to topology *T4*. Regarding the difference between Komondor and CTMNs results, note that successful simultaneous transmissions (or slotted backoff collisions) are allowed in Komondor, as well as the capture effect is accomplished. Henceforth, the throughput is slightly higher in Komondor.

The neighbor overlapping case in topology *T2*, where A and C can transmit at the same time whenever B is not active, but B can only do so when both A and C are not active, is a clear case of exposed-node starvation. Namely, B has very few transmission opportunities as A and C are transmitting almost permanently and B must continuously freeze its backoff consequently.



(a) Topologies (b) Average throughput

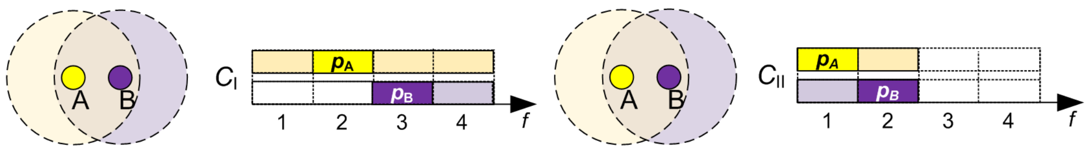
Figure 12: Scenarios and results for Komondor validations. Yellow and blue arrows indicate the carrier sense range of WLANs A and C, respectively (CST is equal for all the APs). The carrier sense range of WLAN B is not displayed. *T3-noCE* refers to topology *T3* when the STA in B does not accomplish the CE condition whenever A, B and C are active. MC and Sim refer to the values obtained through SFCTMN and Komondor, respectively.

Regarding *T3*, the sum of the interference that B perceives when A and C are transmitting at the same time prevents it to decrease the backoff. However, B is able to decrement the backoff any time A or C are not transmitting.

Finally, in topology *T4*, due to the fact that WLANs are isolated, the number of successful parallel transmissions is maximum.

4.4 Dynamic Channel Bonding Validation

Finally, we validate one of the most important techniques included in the Komondor simulator, which is Dynamic Channel Bonding. In order to do that, we introduce the scenarios shown in Figure 13, which consider two overlapping WLANs.



(a) *Scenario I* (b) *Scenario II*

Figure 13: WLANs A and B are inside the carrier sense range of each other with potentially overlapping channels 1 and 2.

In Table 4 we show the results from applying the different DCB policies introduced in Section 3.3. We display the average throughput experienced by WLANs A and B (Γ_{A} and Γ_{B}, respectively), and by the whole network (Γ).

Let us first consider *Scenario I*. As expected, due to the fact that both WLANs overlap in channels 3 and 4 when transmitting in their whole allocated channels, the SCB policy reaches just three feasible states in which WLANs cannot transmit at the same time. In the case of OP both WLANs are forced to pick just their primary channel for transmitting and, therefore, they can transmit simultaneously. Regarding the AM policy, which is usually used as de-facto when applying DCB, it allows simultaneous transmissions provided that WLAN B started transmitting when the channel was idle. Notice that with AM, any time the backoff of an AP in WLAN X expires and the channel is idle, a given AP would pick the the widest available channel. The last policy studied is PU, which is characterized by providing further exploration regarding the possible channel range combinations. In scenario I, whenever the channel is idle and the backoff of either A or B expires, each of the possible available channel ranges may be chosen with same probability. For instance, A may choose channel ranges 2, 1-2 or 1-4 with probability $1/3$. Similarly, B may choose transmitting over channels 3 or 3-4.

Intuitively, one could think that, as it occurs in *Scenario I*, picking always the widest channel found free by means of AM, i.e., maximizing the throughput of the immediate transmission (or

	Scenario I				*Scenario II*			
$\mathcal{D}$	$\lvert\mathcal{S}\rvert$	Γ_A	Γ_B	Γ	$\lvert\mathcal{S}\rvert$	Γ_A	Γ_B	Γ
OP	4	113.23 113.23	113.23 113.23	226.47 226.46	4	113.23 113.23	113.23 113.23	226.47 226.46
SCB	3	143.46 131.98	143.46 148.85	286.92 280.83	3	109.19 108.72	109.19 108.84	218.38 217.56
AM	5	220.12 217.60	212.21 214.81	432.34 432.41	3	109.19 108.72	109.19 108.84	218.38 217.56
PU	10	149.14 149.20	148.38 148.42	297.52 297.63	6	113.19 113.20	113.19 113.18	226.38 226.38

Table 4: DCB policy effect on the average throughput [Mbps] in *Scenario I* and *Scenario II*. The values obtained through Komondor are displayed in blue, while the other correspond to the CTMN model.

short-term throughput), may be the best strategy for optimizing the long-term throughput as well. However, the *Scenario II* depicted in Figure 13b, is a counterexample that illustrates such lack of applicable intuition. Firstly, with OP, due to the fact that WLANs are only allowed to transmit in their primary channel, simultaneous transmissions can be carried out. On the other hand, with SCB, WLANs can only transmit in their complete allocated channel, thus allowing a single transmission at a time. Notice that in this case AM generates the same transition probabilities (and respective average throughput) than SCB because whenever a WLAN has the possibility to transmit. Finally, PU picks uniformly at random any of the possible channel combinations that A and B may choose when terminating their backoff in case that the channel is idle.

Concerning the throughput differences in the values obtained by CTMNs and Komondor, we note that the main disparities correspond to the AM and SCB policies. It is important to remark that while CTMN does not consider neither backoff collisions nor NAV periods, Komondor actually does so in a realistic way. Therefore, in Komondor, whenever there is a slotted backoff collision, the RTS packets can be decoded by the STAs in both WLANs and the average throughputs are increased consequently. Regarding the NAV periods, an interesting phenomena occurs in *Scenario I* when implementing SCB, AM or PU. While the RTS packets sent by B cannot be decoded by A because its primary channel is always outside the transmission channel range of B, the opposite occurs when A sends them. Due to the fact that the RTS is duplicated in each of the basic channels used for transmitting, whenever A transmits in its whole allocated channel, B is able to decode the RTS and enters in NAV consequently.

5 Tutorial and Development Notes

In this Section we provide a brief tutorial to encourage researchers and other practitioners to use the Komondor simulator for their own experiments, and even to participate in the project.

5.1 Brief Tutorial

Komondor is composed by several modules that allow performing simulations with a high degree of freedom. Here we provide some details on the most important modules, as well as on their practical execution. Figure 14 summarizes the main operations carried out by Komondor.

As shown, Komondor receives a set of inputs (nodes information, simulation time, etc.) and initializes the main module, which is in charge of generating the network and gathering useful information regarding the simulation. During the core simulation, nodes interact among each other by sending packets, so that DCF operation is implemented for accessing to the channel. Finally, when the simulation runs out, a set of outputs are generated in order to shed some light on the network performance.

5.1.1 Files Organization

To properly understand the Komondor's operation, it is important to know how the project is organized, which allows obtaining a broader vision of the different modules that constitute it. The code is organized as follows:

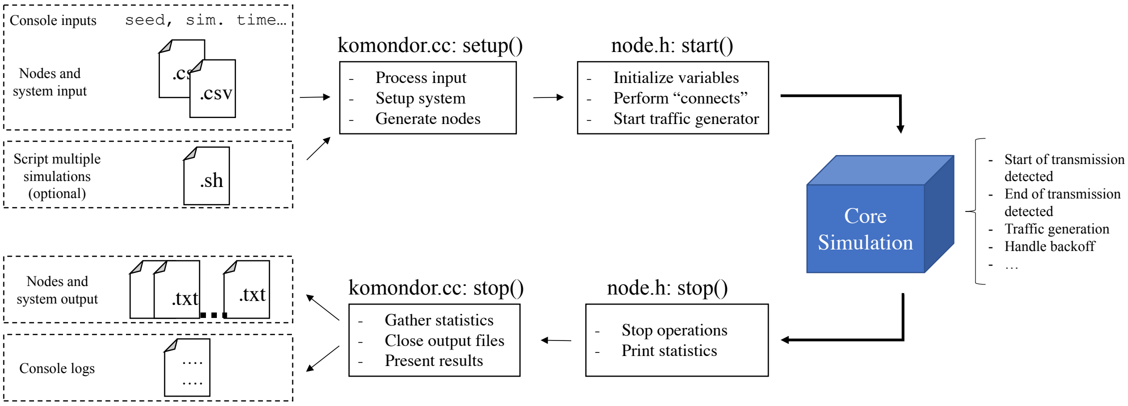


Figure 14: Komondor flowchart

- **COST libraries**: constitute the Komondor's primitive operation.
- **Main**: contains the two core files (`komondor.cc` and `node.h`), which are in charge of orchestrating all the simulation. In addition, here we find the inputs and the file that compiles the libraries for executing the code (`build_local`).
- **Methods**: by following clean architecture guidelines, independent methods used by both `komondor.cc` and `node.h` files are contained in the methods folder. Several libraries are provided according to the nature of their functions. For instance, `backoff_methods.h` contains methods to handle the backoff operation in DCF.
- **Structures**: the Komondor simulator considers four main header files to carry out its operation. The first one is `wlan.h`, which defines the main characteristics of a WLAN (WLAN id, list of associated STAs, etc.). Furthermore, the `notification.h` object allows to exchange packets between devices. Finally, `logger.h` and `logical_nack.h` are used for auxiliary purposes, which are displaying logs and notifying packet losses causes, respectively.
- **List of macros**: all the static parameters (e.g., constants) are contained in the `list_of_macros.h` file.
- **Input**: contains the input files that allow building the simulation environment.
- **Output**: contains the data generated by Komondor as a result of a given simulation.

5.1.2 Compilation and Execution

To compile and execute Komondor, the following instructions must be followed[5]:

1. Set the .csv input files (further defined in Section 5.1.3)
2. Access to the *KomondorSimulator* directory
3. Execute ".build_local". This file contains the instructions for compiling the Komondor code. It has been updated to enable debugging with Valgrind[6].
4. Execute *./KomondorSimulator arg_1 arg_2 ... arg_n*, where *arg_i* is the i_{th} input argument:
   - *arg_1* (INPUT_FILE_SYSTEM_CONFIGURATION): file containing system information (e.g., number of channels available, traffic model, etc.). The file must be a .csv with semicolons as separators.
   - *arg_2* (INPUT_FILE_NODES): file containing nodes information (e.g., position, channels allowed, etc.).The file must be a .csv with semicolons as separators.

[5] A GNU-based OS is assumed to be used for simulations, including basic compilation programs such as *gcc*.
[6] Valgrind is a programming tool for memory debugging, memory leak detection, and profiling. Valgrind main website: http://valgrind.org/

- *arg_3* (OUTPUT_FILE_LOGS): path to the output file to which write results at the end of the execution (if the file does not exist, the system will create it).
- *arg_4* (FLAG_SAVE_SYSTEM_LOGS): flag to indicate whether to save the system logs into a file (1) or not (0).[7]
- *arg_5* (FLAG_SAVE_NODE_LOGS): flag to indicate whether to save the nodes logs into separate files (1) or not (0). If this flag is activated, one file per node will be created.
- *arg_6* (FLAG_PRINT_SYSTEM_LOGS): flag to indicate whether to print the system logs (1) or not (0).
- *arg_7* (FLAG_PRINT_NODE_LOGS): flag to indicate whether to print the nodes logs (1) or not (0).
- *arg_8* (SIM_TIME): simulation time in seconds.
- *arg_9* (SEED): random seed for the experiments.

5. Collect the results either in the output files or in the console.

NOTE: in case that the user does not have permissions to execute some of the files, grant them by introducing the following command in the target folder: `$ chmod -R 777 *`.

5.1.3 Input files

To define the simulation environment, the Komondor simulator relies in the following two types of input files:

- **System input:** defines global input parameters such as the number of basic channels considered or the propagation models. System input parameters are defined in Table 5.
- **Nodes input:** defines specific nodes' characteristics such as type, location, or implementing features (e.g., DCB policy). There are two ways of generating nodes, which is indicated in the file name.
  - In case of including the keyword *nodes*, all the devices (both APs and STAs) must be introduced and described.
  - Otherwise, if including the keyword *aps*, only the APs are defined, so that a set of STAs is randomly generated under certain introduced parameters (e.g., minimum/maximum number of STAs, maximum distance between APs and STA).[8]

As a final remark, in order to ensure a proper execution, it is mandatory to introduce an input file with a list of nodes ordered by *node_id* and starting with $node\_id = 0$ (it is a requirement for the array responsible of storing the power perceived by each node). Table 6 describes the Nodes input parameters for both *nodes* and *aps* files.

5.1.4 Input scripts

In order to facilitate users work, we provide a set of scripts that allow performing several simulations at once, which is useful to avoid processing different output files. Such sample scripts can be found in the "scripts multiple executions" folder, which perform the following operations:

- *multiple_inputs_script.sh*: processes all the input files contained in ./input/script_input_files and generates a simulation for each one.
- *multiple_inputs_script_several_seeds.sh*: in addition to process multiple inputs, generates different seeds for each simulation.

Similar procedures can be implemented to extend the current provided functionalities, such as reading multiple system inputs or generating specific output reports.

[7] Major increases in the execution time may occur if nodes logging is activated. E.g., for a simulation of 4 nodes, simulating 1000 seconds takes 1.127 s and 15.672 s when not logging and when doing so, respectively.

[8] The usage of APs input files is discouraged to the lack of maintenance.

Parameter	Type	Description
num_channels	int	Maximum number of frequency channels in the system
basic_channel_bandwidth	int	Bandwidth for each channel [MHz]
pdf_backoff	int	PDF to compute the backoff ()
pdf_tx_time	int	PDF to compute the tx time ()
packet_length	int	Length of data packets [bits]
ack_length	int	Length of ACK packets [bits]
num_packets_aggregated	int	Number of packets aggregated per transmission
path_loss_model	int	Path-loss model (0: FSPL, 1: Hata, 2: Indoor 1, 3: Indoor 2, 4: TGax scenario 1)
capture_effect	int	Capture Effect Threshold [dB]
noise_level	int	Floor noise level [dBm]
adjacent_channel_model	int	Co-channel interference model (0: without adjacent interference, 1: contiguous adjacent interference, 2: complete adjacent interference)
collisions_model	int	Collisions model (reserved)
SIFS	int	SIFS period [μs]
constant_PER	int	Defines a constant Packet Error Rate
traffic_model	int	Traffic model (0: full buffer, 1: Poisson distr., 2: deterministic distr.)
backoff_type	int	Type of backoff (discrete: 0, continuous: 1)
rts_length	int	Length of RTS packets [bits]
cts_length	int	Length of CTS packets [bits]
cw_adaptation	bool	For activating CW adaptation
pifs_activated	bool	For activating PIFS

Table 5: System input parameters description

5.1.5 Output files

A lot of effort has been put on the output generation, since it is a sensitive module that allows understanding and validating the results provided by the simulator. Henceforth, we provide different kinds of outputs, which refer to console and file output logs. Note, as well, that generating output files considerably increases the execution time.

Regarding console output logs, them can be activated through *arg_6* and *arg_7* during the execution, which refer to system and nodes logs, respectively (see Section 5.1.2). Additionally, these logs can be copied into files, which are saved into the *output* folder, only if *arg_4* and *arg_5* are set to 1. While the path of the system's output file must be specified (*arg_3*), nodes' files are automatically created.

Finally, a set of statistics are shown per node and for the entire simulation. Such statistics include throughput experienced, collisions, nodes sent, RTS/CTS sent, etc. An example of nodes and system statistics is shown in Figures 15 and 16

5.1.6 Events Categorization

In order to make output results more understandable, logs are categorized according to the event that generates it. With that, further filtering processes can be carried out by developers. Table 7 describes the codes used for each type of event.

5.2 Code development

Here we provide some clarifications regarding code implementation, wit the aim to facilitate the Komondor's usage and manipulation to developers that may be interested.

Parameter	Type	Nodes or APs	Description
node_code	String	nodes	Code assigned to the node
node_type	int	nodes	Type of node (0: AP, 1: STA)
wlan_code	String	both	Code assigned to the WLAN
destination_id	int	nodes	To specify the ID of the destination (packets would be only sent to that devices). Setting it to -1 indicates random destination.
min_sta_number	int	aps	Minimum number of associated STAs
max_sta_number	int	aps	Maximum number of associated STAs
max_distance_sta	int	aps	Maximum distance of associated STAs
x	int	both	X location [m]
y	int	both	Y location [m]
z	int	both	Z location [m]
primary_channel	int	both	Primary channel
min_channel_allowed	int	both	Left channel in range
max_channel_allowed	int	both	Right channel in range
cw	int	both	Fixed CW
cw_stage	int	both	Initial CW stage (for CW adaptation)
tpc_min	int	both	Minimum transmit power allowed [dBm]
tpc_default	int	both	Default transmit power allowed [dBm]
tpc_max	int	both	Maximum transmit power allowed [dBm]
cca_min	double	both	Minimum CCA allowed [dBm]
cca_default	double	both	Default CCA allowed [dBm]
cca_max	double	both	Maximum CCA allowed [dBm]
tx_antenna_gain	int	both	Gain of the tx antenna [dB]
rx_antenna_gain	int	both	Gain of the rx antenna [dB]
channel_bonding_model	int	both	Channel bonding model (0: only primary, 1: SCB, 2: SCB log2, 3: always max, 4: always max log2, 5: always max log2 MCS, 6: uniform probability log2)
modulation_default	int	both	Modulation set by default (0 to use dynamic MCS)
central_freq	int	both	Frequency band used (2,4 or 5 GHz)
lambda	float	both	Packets transmission rate [packets/s]
ieee_protocol	int	both	IEEE protocol used

Table 6: Nodes input parameters description

5.2.1 Main considerations

Some technical information regarding code development is worth to be mentioned to properly understand how to use and modify the Komondor simulator. So far, the main considerations to be taken into account are:

- **Power and CCA**: power variables are stored in pW (pico watts) in order to be able to operate power magnitudes without loosing resolution[9]. However, values are presented to the user in dBm. W (-30) - mW (0) - uW (+30) - nW (+60) - pW (+90)
  $P_{\text{pw}} = 10^{\frac{P_{\text{dBm}}+90}{10}}$

5.2.2 Miscellaneous

- **Transmitting capability**: we have added a flag to each node that determines if it is able to transmit (1) or not (0), so that we can decide if the node is only listening or both transmitting and listening.

[9]For instance., the sum of two signals of power values -85 dBm (3.162 pW) and -90 dBm (1 pW), respectively, is -83.803 dBm (4.162 pW).

```
------- AP_A (N0) ------
  - Throughput = 102.120960 Mbps
  - RTS/CTS sent = 14750 - RTS/CTS lost = 0  (0.00 % lost)
    · RTS lost due to slotted BO = 0 (0.000000 %)
  - Data packets sent = 14750 - Data packets lost = 1453  (9.850847 % lost)
  - num_tx_init_tried = 14750 - num_tx_init_not_possible = 0 (0.000000 % failed)
    · Time EFFECTIVELY transmitting in N channels:
    · - 1: 86.849472 s (86.85 %)
    · Time EFFECTIVELY transmitting in each channel:
    · - 0 = 86.87 s (86.87 %)
    · - 1 = 0.00 s (0.00 %)
    · Number of tx trials per number of channels:
    · - 1: 14750 (100.00 %)
    · - 2: 0 (0.00 %)
  - num_tx_init_not_possible = 0


------- AP_B (N2) ------
  - Throughput = 101.798400 Mbps
  - RTS/CTS sent = 14751 - RTS/CTS lost = 0  (0.00 % lost)
    · RTS lost due to slotted BO = 0 (0.000000 %)
  - Data packets sent = 14750 - Data packets lost = 1495  (10.135593 % lost)
  - num_tx_init_tried = 14751 - num_tx_init_not_possible = 0 (0.000000 % failed)
    · Time EFFECTIVELY transmitting in N channels:
    · - 1: 86.581660 s (86.58 %)
    · Time EFFECTIVELY transmitting in each channel:
    · - 0 = 0.00 s (0.00 %)
    · - 1 = 86.61 s (86.61 %)
    · Number of tx trials per number of channels:
    · - 1: 14751 (100.00 %)
    · - 2: 0 (0.00 %)
  - num_tx_init_not_possible = 0
```

Figure 15: Example of nodes statistics in Komondor

```
 General Statistics:
  - Total number of packets sent = 58999
  - Total throughput = 408.27 Mbps
  - Average number of packets sent per WLAN = 14749
  - Average throughput per WLAN = 102.07 Mbps



- Average throughput per WLAN = 102.07 Mbps
- Proportional Fairness = 32.04
- Jain's Fairness = 1.00
- Average number of data packets successfully sent per WLAN = 14749.75
- Average number of RTS packets lost due to slotted BO = 0.00 (0.00 % loss)

------ FOR COMPARING TO BIANCCI -------
- Prob. collision by slotted BO = 0.000000
- Aggregate throughput = 408.268800 Mbps
- Aggregate number of transmission not possible = 0
---------------------------------------


    · - 1: 14750 (100.00 %)
    · - 2: 0 (0.00 %)
    · - 1: 14751 (100.00 %)
    · - 2: 0 (0.00 %)
    · - 1: 14750 (100.00 %)
    · - 2: 0 (0.00 %)
    · - 1: 14749 (100.00 %)
    · - 2: 0 (0.00 %) SIMULATION 'test' FINISHED
------------------------------------------
# -------------------------------------------------------------------------
# CostSimEng with SimpleQueue, stopped at 100.000000
# 590007 events processed in 3.920 seconds, event processing rate: 150523
administrador@ws119785:~/workspace/Komondor/Code/komondor_main$ S
```

Figure 16: Example of system statistics in Komondor

- **Progress bar**: the Komondor simulation progress bar is displayed through a *printf()* command called by any node with *node_id* set to 0. If no node has *node_id* set to 0, the progress bar is not displayed.

Method	Type	Sub-type	Event description
Setup()	A	-	-
Start()	B	B00	Start()
		B01	Start() end
		B02	Node's info (one line)
Stop()	C	C00	Stop()
		C01	Stop() end
		C02	Time transmitting in number of channels
		C03	Time transmitting in each channel
		C04	Packets sent
		C05	Throughput
inportSomeNodeStartTX()	D	D00	inportSomeNodeStartTX()
		D01	inportSomeNodeStartTX() end
		D02	Node N has started a TX in channels: c_left - c_right
		D03	Pre update channel state
		D04	Distance to transmitting node
		D05	Power received from transmitting node
		D06	Post update channel state
		D07	I am (or not) the TX destination
		D08	Current SINR
		D09	Capacitiy
		D10	Primary channel affected (or not)
		D11	Power sensed in primary channel
		D12	CCA exceeded (or not)
		D13	Backoof active (or not)
inportSomeNodeFinishTX()	E	E00	inportSomeNodeFinishTX()
		E01	inportSomeNodeFinishTX() end
		E02	N%d has finished a TX in channel range: %d - %d
		E03	Initial power of transmitter
		E04	Pre update channel state
		E05	Post update channel state
		E06	Primary channel affected (or not)
		E07	Power sensed in primary channel
		E08	CCA exceeded (or not)
		E09	I am transmitting (or not)
endBackoff()	F	F00	endBackoff()
		F01	endBackoff() end
		F02	Channels for transmitting
		F03	Transmission is possible (or not)
		F04	Selected transmission range
		F05	New backoff generated
myTXFinished()	G	G00	myTXFinished()
		G01	myTXFinished() end
		G02	New backoff generated

Table 7: Node's event logs encoding

6 Conclusions

In this document we provided an overview of the first version of the Komondor simulator, which aims to reproduce the basic operation of IEEE 802.11ax WLANs in addition to allow the utilization of intelligent systems. We introduced the system model considered when building the simulator, as well as the main MAC features implemented. Additionally, due to the open source nature of this project, we provided basic information of interest for developers that are expected to use or even modify this HD WLANs simulator.

Regarding the validation of the simulator, we provided a set of meaningful test scenarios to prove the proper behavior of the simulator. As shown, tests were satisfactory as the throughput computed with Komondor and the CTMN model are pretty similar, and the differences were properly justified.

This project is expected to move forward for including of novel mechanisms such as OFDMA, MU-MIMO, TPC or CST adjustment. In addition, intelligent agents are expected to be included for making operations such as Dynamic CB (DCB).

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