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ORIGINAL ARTICLE

IEEE 802.11 graph models

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Abstract There are several recent research lines addressing Wi-Fi network planning and optimization, both in terms of channel assignment and access point deployment. The problem with these works is that evaluation is usually performed with specific and closed models regarding signal propagation, throughput computation, and utility definition. Also, many of the models in the literature make assumptions about the role of wireless stations, or the co-channel interference, which -while being valid in the context of a single research work- makes very difficult to compare different approaches, to re-use concepts from previous mechanisms to create new ones, or to generalize mechanisms to other scenarios. This makes the different research lines in Wi-Fi network planning and optimization progress in an isolated manner.

This paper aims to address such a recurring problem by proposing a graph-based generic model for Wi-Fi utility computation in network planning scenarios, as well as providing a collection of scenario graphs which may be used to benchmark different planning and optimization approaches. Experiments are conducted to show the validity of the model and the significance of its features, along with its extensibility to other scenarios.

1. Introduction

Coexistence of multiple wireless networks and users competing for the scarce resources of the radio electric spectrum is a complex problem demanding attention from the research community. Independent evolution and management of these networks have yielded an undesirable situation: most wireless networks are highly inefficient in many cases [1]. This is being addressed by the researchers from two different perspectives. On one hand, devising new standards and specifications for high-efficiency wireless local area networks (HEWs) [1]. On the other hand, improving planning, coordination, and optimization mechanisms for the existing standards.

In the latter case, a variety of approaches have been proposed, yielding promising results in a wide range of scenarios [2–6]. However, most of these approaches are evaluated with

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specific models not easily portable to other settings. Therefore, a recurrent challenge researchers have to face is how to justify the models and mechanisms they propose, or how to compare their approaches and methods with the ones of other researchers. In the best cases, there are a few number of previous works similar enough to the new proposal to make a comparison. In most cases, however, this comparison is not possible due to the diversity of the models the different research groups deal with, so the different research lines progress in an isolated manner.

This paper intends to bridge this gap by proposing a generic model suitable to be applied to different problems of Wi-Fi planning, coordination, and optimization, in order to enable comparison between different approaches in a usable and reproducible way. Our choice of a model is not arbitrary, and is motivated by the advantages and disadvantages of the different possibilities. Apart from using prototypes or real networks, which are expensive and difficult to set up, researchers usually resort to analytic and simulation models to design and evaluate the performance of telecommunication networks [7]. Each kind of approach operates from a different abstraction level, and therefore has its own advantages and drawbacks. While network simulators are able to capture a higher number of features, analytic models are faster and capture the essence of the feature under study, isolating it from the rest of features. Regarding drawbacks, analytic models are very limited by the underlying mathematical processes, while simulation models are computationally costly and usually not attractive to researchers due to the complexity of the underlying procedures (usually unknown to the researchers). Due to their advantages and disadvantages, the use of analytic and simulation methods coexist and complement each other. In fact, it is usual to initiate the studies with analytic models and evaluate them later via simulation before their implementation or commercial exploitation.

The proposed model is suitable for a wide range of wireless networks settings. However, we have focused our attention on those layouts where the high density of wireless devices makes coordination and optimization even more necessary to be able to obtain a satisfactory quality of service. These high-density settings are usually named dense or ultra-dense Wi-Fi networks and are being thoroughly studied by the scientific community [8,9] because, if not properly designed and optimized, they can become highly inefficient. In fact, the proposed model includes the paradigmatic issues that drive dense Wi-Fi networks to be inefficient. For example, dense Wi-Fi network models must be three-dimensional, as the interferences to a signal may come from any directions. Moreover, they must consider co-channel interferences, i.e. interferences from overlapping channels, as they can become very harmful and, therefore, they must not be ignored. Additionally, we consider that dense settings occur specially in indoor environments, so our model includes a realistic indoor propagation and loss model which considers obstacles. However, although we have tailored the model to include the most challenging features in Wi-Fi networks, the high expressiveness and flexibility of the model makes it also suited to be used for simpler settings and also to be extended to other situations. For example, to consider an outdoor layout we would only need to change the propagation and loss model. Or if, as in many previous works [10], we want to restrict the study to orthogonal Wi-Fi channels, we can directly use those and there will not be any kind of co-channel interferences. Finally, the expressiveness of the model makes it useful to be the basis for more specific studies, like the consideration of channel bonding [11].

This paper proposes, to the best of our knowledge, the first generic model for Wi-Fi settings including realistic indoor signal propagation for three-dimensional settings, taking into account the precise location and interferences between all wireless devices (both APs and STAs), and considering co-channel interference among all available channels in Wi-Fi. The model makes contributions in four lines:

- We describe a model for IEEE 802.11 wireless communications, including architecture, signal propagation and interference, and throughput computation. The model integrates data from different sources, including the ITU propagation model, studies about indoor propagation and co-channel interferences and data about the relationship between Signal-to-Interference-plus-Noise Ratio (SINR) and actual throughput.
- We propose a graph-based modeling of realistic, three-dimensional scenarios, along with a collection of settings we put at the disposal of the research community. These settings represent realistic scenarios of dense Wi-Fi networks in residential buildings of multiple floors. These graphs can be used by the community for benchmarking, so that they can compare different approaches (e.g. their own against the ones in the state-of-the-art) in the same conditions.
- We conduct a comprehensive set of validation experiments, first with simple graphs that allow to check the validity and consistency of the model and then with the generated realistic settings, to assess the significance of the model properties. We can see there is a significant effect of the inclusion of vertical distance attenuation, co-channel interference, STA density and tri-dimensional layout, which makes this model more accurate and realistic than the ones used in previous works.
- We present two examples on how the model can be easily extended to accommodate other technologies. In particular, we adapt the model to channel bonding in Wi-Fi 5, and also to the study of the impact of the coexistence with Bluetooth devices.

The rest of this paper is organized as follows. The next section gives context to our proposal and frames it in the state of the art. Then, Section 3 describes our model for IEEE 802.11 wireless communication. Afterwards, Section 4 presents the scenario modeling based on graphs. Once the communication model and scenarios have been established, the experimental evaluation is described in Section 5. Finally, Section 6 briefly discusses our contributions and identifies lines for future research. As Supplementary Material, we provide the graphs for the generated scenarios, and we make the code for throughput computation using our model available upon request.

2. Related Work

There are a number of analytical and simulation models for wireless networks in the literature, some of which we have worked with in the past [12,13]. However, the diversity and high specificity of the models proposals for channel selection in WLANs makes very difficult to compare approaches [2].

Graph-based modeling has been widely used to model communication networks [14,15], specially for wireless networks [16–19]. However, their use for WLAN networks has been more limited [20,21]. Graph models in Wi-Fi (or wireless communications in general) have been used for frequency assignment problems (FAP) [22], specially when the problem has been studied as an instance of a graph coloring problem [16,23].

In the following, we describe some of the most prominent works that use graph models in the context of Wi-Fi networks. In [24], authors deal with a channel assignment problem considering interferences between APs, and they propose a weighted variant of the well-known graph coloring problem with realistic channel interference. Although [25] considers STAs in the channel assignment procedure, the proposed model does not include STAs as vertices in the graph, but it includes their effect by adding interference edges between APs when any of their associated STAs interfere. Similarly, in [4] authors propose a centralized channel assignment based on clusters to minimize the interference level at APs. In [26], we studied the channel assignment problem in Wi-Fi planar scenarios analyzing the effect of using only orthogonal Wi-Fi channels. Authors in [27] use machine learning for channel allocation in Wi-Fi networks using a simple graph model. In their model, vertices represent APs and edges between them exist provided both APs detect each other when scanning the spectrum. In [28], Stojanova et al. propose a graph model for Wi-Fi networks to measure performance using a Divide-and-Conquer strategy to break down the original problem into several sub-problems, and later combining the solutions to solve the whole original problem. In [10], authors propose both exact and heuristic wireless channel assignment techniques in the field of hybrid data center networks, thus enabling high throughput in wireless and wired transmissions. In this graph model, vertices represent communications between different transmitters and edges represent interference signals. The work described in [29] models a wide variety of Wi-Fi networksby means of graphs, and then computes some of their main features like selected centrality metrics. In [30], authors propose an enriched version of a conflict graph to model Wi-Fi networks, so it represents the partial conflicts (interference, detections…) between the devices in the Wi-Fi network, but it does not include STAs. In a similar way, [31] uses two conflict graphs (a physical one and a logical one) to study channel bonding in Wi-Fi networks, in. The vertices of the physical conflict graph represent APs and the edges represent the fact that two APs are neighbors, while the logical conflict graph depends on the channel assignment and, therefore, on the logical neighbors.

Once we have described the most outstanding or recent approaches in the field of graph modeling for Wi-Fi networks, we now describe and justify the need of our proposed graph model. Although the graph models we have found in the literature are valid for the purposes of each specific paper where they appear, they have different limitations which make them unsuitable for generic use and comparison among different researchers. Many of them use graphs that make unrealistic simplifications on the Wi-Fi propagation model, such as assuming on–off signal reception, that is, two wireless devices being either "in range", and therefore fully receiving each other's signal, or "out of range", and therefore not interfering at all [24]. Those which use a more realistic propagation model, such as [10,29], restrict the analysis to a limited set of available channels (3 or 4), hence ignoring co-channel interference, which is one of the most prominent aspects of Wi-Fi networks, as we have discussed in our previous work [32]. Moreover, our model is, up to our knowledge, the first graph-based model that uses a realistic indoor propagation model like the one described by ITU in Recommendation P.1238 [33]. On the other hand, although it is a wide belief in the community that Wi-Fi assignments using only orthogonal channels yield better results, this has only been studied for settings with planar scenarios [26]. However, most of the realistic settings where Wi-Fi networks are deployed, such as residential buildings or offices, are three-dimensional, where wireless devices in different floors may interfere with each other. Finally, models in the literature usually do not take into account the wireless stations (STAs), considering only the access points (APs) [4,27,28,30,31], or modeling the effect of STAs in a simplified manner (e.g., by assuming that two APs also interfere if two of their clients are in range of each other, but without taking into account signal propagation between them) [34].

Taking all this into account, we have developed a streamlined, flexible and reusable yet accurate generic Wi-Fi model framework that can be used by other researchers to propose, implement, evaluate and compare their work with other state of the art proposals. In addition, our framework lays somewhat in the line between analytic and simulation models. We discarded the use of pure analytical models (such as the one described by a queueing network or a Markov process) because the complexity of Wi-Fi networks as a whole makes it very difficult to analytically solve them. In the same sense, we discarded to use a discrete event simulator for Wi-Fi due to its high computational cost and the fact that the high number of parameters that a simulator requires makes the scientific proposals not easily replicated. Finally, most commercial simulators do not consider adjacent channel interferences [35], which are specially critical in dense settings. So we propose a model which is closer to simulation than the usual analytical models, but that is usable and flexible enough to be used for comparison in the earlier and middle stages of research, prior to implementation, where simulators are definitely needed for final tuning.

3. Modeling IEEE 802.11 wireless communications

3.1. IEEE 802.11 architecture

Wi-Fi networks are composed of two different devices: access points (APs) and stations (STAs). Although Wi-Fi networks can also operate in *ad hoc mode*, we focus in the most widely used operation mode, which is *infrastructure* mode. In this mode, communication always occurs between an AP and a STA, since direct communication between STAs is not permitted. Therefore, to provide connectivity to STAs, they must be associated to an AP. For that reason, in this operation mode, Wi-Fi networks can be seen as a set of *clusters*, where each cluster is an organizational structure made up of an AP and all its associated STAs. Fig. 1 shows an example of a Wi-Fi network operating in infrastructure mode composed of 16 APs (large green circles) and 54 STAs (small black squares), where the concept of Wi-Fi cluster can be clearly observed.

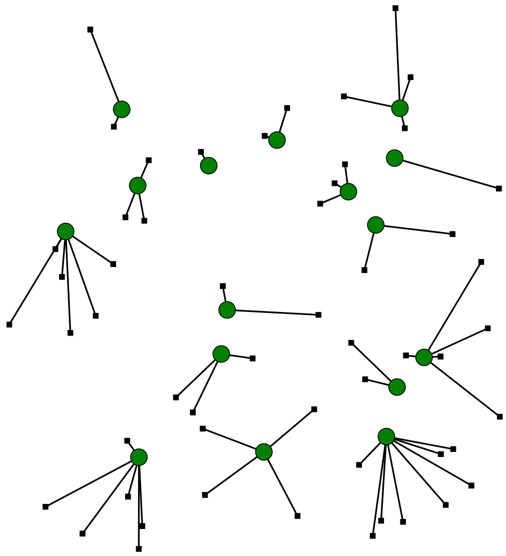


Fig. 1 Example of Wi-Fi deployment using infrastructure mode.

Without loss of generality, in this paper we model the IEEE 802.11n standard (recently renamed as Wi-Fi 4) operating in the 2.4 GHz frequency band with 20 MHz channels. However, the model is not restricted to a specific technology, since it is an intermediate abstraction level between analytical models and discrete event simulations. For that reason, and for example, it would be straightforward to use the model for IEEE 802.11ax (Wi-Fi 6) by tuning the configuration parameters. The reason of choosing the 2.4 GHz frequency band is because it is the most congested of the unlicensed frequency bands, which makes it specially challenging for network planning and optimization.

3.2. Signal propagation and interferences

To describe how wireless signals propagate, we have used the model defined by the ITU-R in Recommendation P.1238–10 [33], which describes an indoor transmission loss model for APs and STAs in the same building. Note that this model also considers the losses produced when the signal traverses different building floors. In [33], propagation losses expressed in dB are defined as:

$$L_{total} = 20\log_{10} f - 28 + N\log_{10} d + L_f(n), \tag{1}$$

where f is the frequency in MHz, N is the distance power loss coefficient, d is the distance between transmitter and receiver in meters and $L_f(n)$ is the floor penetration factor when signal traverses n floors. As previously mentioned, we have focused our attention in the most widely used 2.4 GHz frequency band, as it is the most congested one. However, it would be straightforward to consider another frequency band like 5 GHz. For the frequency band considered here, [33] specifies a value of $N = 28$ for residential environments. However, it is also admitted in [33] that propagation through walls increases the power loss coefficient considerably, using as examples paths between rooms in closed-plan buildings. For that reason, and according to [36], we have used $N = 28$ when $d < 16$ meters and $N = 38$ for $d \geqslant 16$ meters. Moreover, we have considered $L_f(n) = 10n$, since [33] states that losses across two floors in residential environments are 10 dB when using concrete. With these values, propagation losses in indoor environments only depend on the distance and the number of floors traversed.

Once wireless signal propagation losses have been defined, we can derive the signal power (in dBm) received by a wireless device i (AP or STA) from the signal transmitted by a wireless device j, as:

$$P_r^{j \to i} = P_t^j + G_j + G_i - L_{total}, \tag{2}$$

where P_t^j stands for the transmission power of Wi-Fi device j (expressed in dBm) and G_j and G_i represent the transmission and reception antenna gains, respectively, both expressed in dB.

Signals that are received by a wireless device can either be the desired signal or an interference (undesired) signal. In the latter case, the power of such an interference will also be affected by two other factors. First, we consider that, due to the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism used in Wi-Fi, APs and STAs cannot transmit continuously. To account for that issue, some studies [37] have modeled that mechanism as a continuous time Markov chain (CTMC). As a result, when both STAs and APs want to transmit a packet with probability P_{STA} and P_{AP}, respectively, they will succeed with a certain probability P_s. Also, P_{AP} is assumed to be greater than P_{STA}, as the amount of data transmitted by APs is expected to be higher than that of the STAs. Both phenomena are included in our model by means of a factor ψ, considering that this factor is different for APs and STAs ($\psi_{STA} = P_{STA} \cdot P_s$ and $\psi_{AP} = P_{AP} \cdot P_s$). Second, we consider that interferences are not always in the same frequency channel, but they can be in any other channel whose spectral mask collides with the frequency channel that the receiver is using. This effect is one of the most prominent peculiarities of Wi-Fi networks, as frequency channels where wireless devices can operate are partially overlapped, and the interference is higher the closer the channels are in the spectrum. More specifically, we use the factor $\kappa(|c_j - c_i|)$ to represent the co-channel interference of two interfering wireless devices using channels c_j and c_i respectively, where $|c_j - c_i|$ is the "distance" (in frequency terms) between the channels. To account for this co-channel interference we have used the values defined in [38], as shown in Table 1.

Including these two factors in the received power of interference signals, we can compute the received interference power at device i due to the signal emitted by device j as (in linear scale):

$$I^{j \to i} = P_r^{j \to i} \cdot \psi \cdot \kappa(|c_j - c_i|). \tag{3}$$

3.3. Throughput computation

Once the power of the desired signal and received interferences is defined, we can compute the Signal-to-Interference-plus-Noise Ratio (SINR) in each device. To compute SINR experienced at a certain wireless device i whose desired signal comes from a device χ, we use the following ratio:

$$SINR_i = \frac{P_r^{\chi \to i}}{\sum_{\forall j \in \mathscr{J}} I^{j \to i} + N}, \tag{4}$$

Table 1 Spectral overlap between Wi-Fi channels [38].

$\lvert c_j - c_i \rvert$	0	1	2	3	4	5	$\geqslant 6$
$\kappa(\lvert c_j - c_i \rvert)$	1	0.8	0.5	0.2	0.1	0.001	0

where $P_r^{\chi \to i}$ is the received power of the desired signal, $\mathscr{J}$ is the set of devices that emit interference signals and N is the power of the thermal noise. To compute N (expressed in dBm) we use the equation:

$$N = -174 + 10\log_{10}(\Delta f), \tag{5}$$

where Δf is the bandwidth of the channel used expressed in Hertz. As we consider the use of 20 MHz channels, we have a thermal noise of $N = -101$ dBm.

Wi-Fi networks use an adaptive modulation and coding scheme (MCS) that depends on the available SINR, having a set of predefined MCSs defined by an index. Then, depending on the MCS in use, we will have a certain throughput. Obviously, as the SINR is higher we will be able to use modulations with a higher number of bits per symbol and coding schemes with a higher proportion of useful information (or less redundant information), which will yield better throughputs.

As mentioned above, we have focused on Wi-Fi 4 [39] using 20 MHz channels. Within Wi-Fi 4, there is another parameter which is relevant to define the achievable throughput for each MCS: the Guard Interval (GI), that represents the pause between packet transmission. Wi-Fi 4 defines two possible Guard Intervals, 400 ns and 800 ns. Although the achievable throughput is higher with the shortest GI, we are focusing on GI = 800 ns, since it is the mandatory option that must be implemented and is widely used as the default value. Finally, provided a certain channel bandwidth and a GI, we have to define the different SINR thresholds that determine the use of a certain MCS. For that purpose, we have used the values from [40]. Table 2 shows the relation between MCS, SINR and throughput. It is important to highlight that STAs have two different throughput values: downlink and uplink. Downlink throughput is related to the information emitted by the AP that is sent to the STA, so it can be computed measuring at the STA the SINR of the signal from the AP to the STA. Analogously, uplink throughput is computed using the SINR of the signal from the STA to the AP measured at the AP. Finally, we have also considered that if the desired signal power ($P_r^{\chi \to i}$) is below the sensitivity of the receiver ($\mathscr{S}$), the throughput is zero, so it will not be necessary to evaluate interference and noise power.

4. Model proposal

4.1. Graph model

Once we have described the models used for computing the throughput achieved by the different network elements composing the Wi-Fi network, we can now define specific layouts that represent realistic Wi-Fi deployments. To model Wi-Fi network layouts weuse geometric undirected graphs.

A graph can be defined as a pair (V, E), where V is a set of vertices, and E is a set of edges between the vertices $E \subseteq \{(u, v) | u, v \in V\}$. In our proposal there are two types of vertices, corresponding to the two types of wireless devices we can find in Wi-Fi infrastructure networks: access points (APs) and stations (STAs). We use geometric graphs, so that each vertex in the graph has a position corresponding to the location of its corresponding wireless device in the network deployment. In addition to having two types of vertices, we also have two types of edges, as edges can represent either the association between APs and STAs or the interference between wireless devices. Since our graph will only represent symmetrical information, like the distance between vertices, we use undirected graphs. However, actual interferences are not symmetrical, because of the factor ψ (see Section 3.2).

In the proposed graph, if two wireless devices are associated (one of them must be an AP and the other a STA) they will be linked by an edge of type *signal*. An AP and all its associated STAs belong to the same *signal cluster*. A vertex v will be linked by an edge of type *interference* to each of the vertices of the graph that belong to a different signal cluster.

Table 2 Relation between MCS, SINR and throughput in Wi-Fi 4 using 20 MHz channels with mandatory 800 ns GI [39].

MCS index	Modulation scheme	Coding rate	Throughput (Mbit/s)	SINR range (dB) [40]
0	BPSK	1/2	6.5	[6.8, 7.9)
1	QPSK	1/2	13.0	[7.9, 10.6)
2	QPSK	3/4	19.5	[10.6, 13.0)
3	16-QAM	1/2	26.0	[13.0, 17.0)
4	16-QAM	3/4	39.0	[17.0, 21.8)
5	64-QAM	2/3	52.0	[21.8, 24.7)
6	64-QAM	3/4	58.5	[24.7, 28.1)
7	64-QAM	5/6	65.0	$\geqslant 28.1$

One of our aims is to propose a Wi-Fi graph model which produces graphs that are easily usable by other researchers. To show this and to explain the internal structure of the proposed model, Fig. 2 shows two complementary representations of the graph model corresponding to an example deployment with only two APs and two STAs per AP. On the left, we show the association relationships between APs and STAs, and the properties related to each vertex element in the graph model. We can see that, in addition of the key that unambiguosly identifies every vertex, vertices have the property *pos* to include their position in the space, defined by three coordinates. In addition, the property *floor* determines the floor of the building where the vertex is. Moreover, the property *type* determines if the vertex is an AP or a STA. Finally, for APs we have property *listSTA*, which is a list of the keys of all its associated STAs. On the other hand, for STAs we have property *associatedAP*, containing the key of the AP the STA is associated to. Fig. 2, on the right, shows the signal/interference information from the perspective of STA-3, and also the properties related to edges in the graph model. We can see that edges have the *dist* property, representing the distance between the two vertices connected by the edge. Moreover, property *type* determines if an edge represents an association AP-STA (then the value is *signal*) or if it is an *interference*. It is important to highlight that new properties can be easily added to vertices and/or edges after loading the graphs, to support the different applications or problems for which the model can be used. Examples of such properties could be the Wi-Fi channel where each vertex operates, which could be added to each vertex in the graph, or the power losses for each edge in the graph, which could be added to edges. This makes easy for researchers to use their available code for their coordination or optimization mechanisms in our model.

4.2. Wi-Fi scenarios modeled

In this subsection we describe the specific layouts of the graph models proposed. To download these graph models, please see the "Supplementary materials" section. The generated graphs represent a realistic setting of 5-floor residential buildings, a paradigmatic example of a dense Wi-Fi network. Each floor has a dimension of $40 \times 30 \times 3$ meters (length, width and height respectively) and has eight flats in a 4×2 arrangement. As usual in residential layouts, in each flat there is a single AP. However, the number of STAs in each flat (η) varies. We have designed graphs with values of η ranging from 1 to 12 to represent a wide range of density of STAs. In all cases, every STA inside a flat is associated to the AP of the same flat. The position of both APs or STAs in the x- and y-axis is randomly generated from a uniform distribution bounded to the limits of the corresponding flat. Regarding the z-axis, each AP or STA is randomly located according to a normal distribution with mean 1.5 meters and a standard deviation of 0.5 meters, also bounded by the floor limits. To summarize, the number of APs in all graphs is equal to $8 \times 5 = 40$ APs, while the number of STAs ranges from 40 (when $\eta = 1$) to 480 (when $\eta = 12$). Finally, for each value of η we have generated 10 different settings, for a total of 120 scenarios.

For the sake of space, we only show a graphical representation of six of the total 120 scenarios generated. More specifically, Fig. 3 shows one sample scenario for several values of η, being η the number of STAs per AP. Fig. 3 only depicts the edges between vertices that represent the association between APs and STAs, avoiding, for the sake of clarity, the representation of interfering signals. To provide a more in-depth representation, we focus on the simplest scenario shown in Fig. 3, i.e., in the layout where $\eta = 2$. For that scenario, Fig. 4 shows the graph representation as projections to the different axes to be able to analyze the graph under different points of view.

Note that Figs. 3 and 4 do not show the interferences between Wi-Fi devices. To show the high number of interferences that appear even in the simplest scenarios ($\eta = 2$), we include two different representations in Fig. 5. Fig. 5a shows the interference edges (in red) produced by a single STA (in blue, with the edge to its associated AP also shown in blue). However, to have an idea of the whole graph including all associations and interferences, we can resort to Fig. 5b, where the very high density of interferences even for $\eta = 2$ is shown.

5. Experimental evaluation

In this section we validate the proposed Wi-Fi model under a variety of situations. First, we use a very simple graph to understand how the model operates and to check its consistency. Later, we make some experiments with the abovemen-

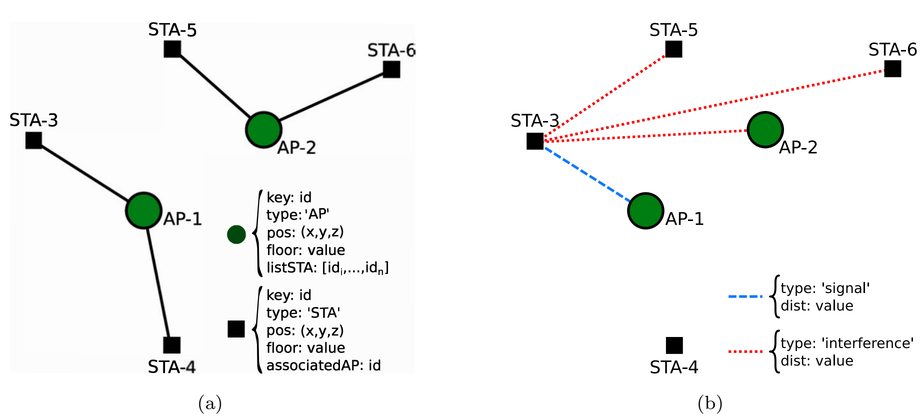
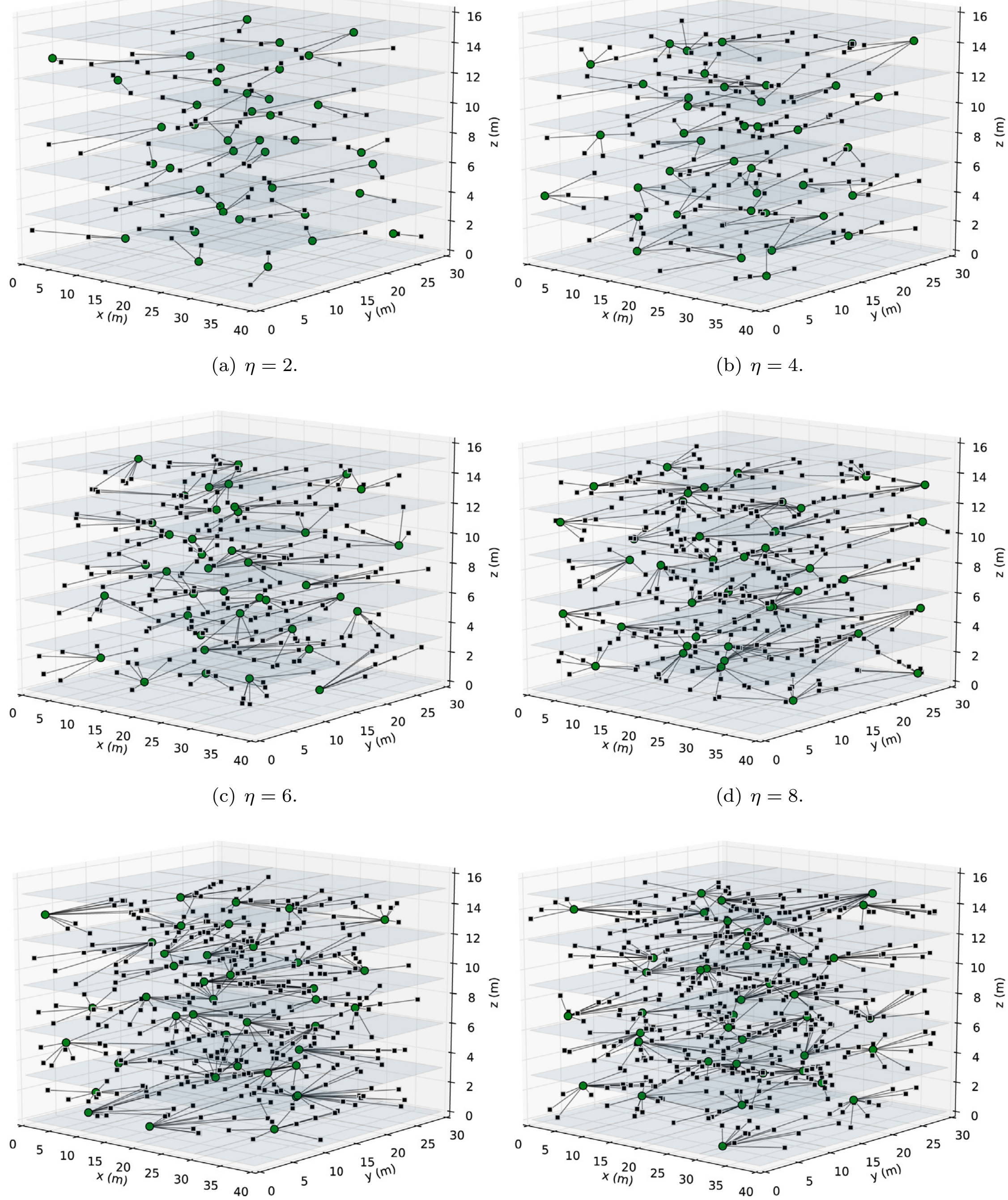


Fig. 2 Illustrative example of the Wi-Fi graph model and properties: (a) AP-STA associations and vertex properties; (b) signal/interference information from the perspective of STA-3 and edge properties.



(a) $\eta = 2$. (b) $\eta = 4$.

(c) $\eta = 6$. (d) $\eta = 8$.

(e) $\eta = 10$. (f) $\eta = 12$.

Fig. 3 Representation of some of the layouts modeled.

tioned 5-floor building graphs and evaluate the performance of the model as well as the significance of some of the features that it incorporates, such as the three-dimensional layout or the co-channel interference. Finally, we show the flexibility of the model by extending it to handle two additional different scenarios: channel bonding in Wi-Fi 5 and interferences due to te coexistence with Bluetooth devices.

Our model, in order to be easily used by other researchers, does not include a high number of parameters to be set up. However, there are some minimal ones that must be tuned. Although this configuration can be very easily changed by the user, in Table 3 we provide a reference for these parameters. Note that these reference values have been chosen for being either typical or reasonable values, and are the ones used in the sections that follow. The different parameters that are shown in Table 3 are the transmission power of wireless devices (P_t), the gain of the transmitting and receiving antennas (G_t and G_r respectively), the sensitivity of the receiver

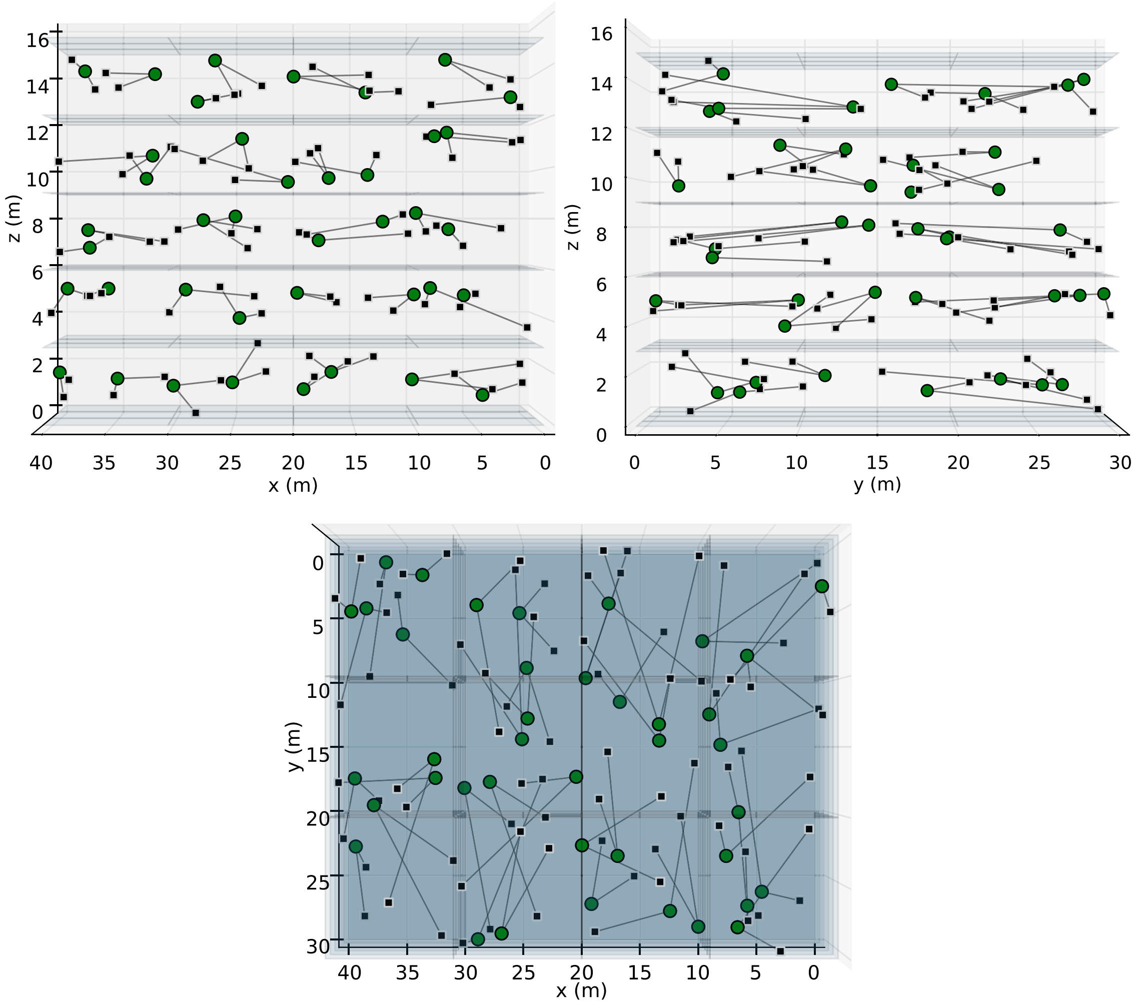
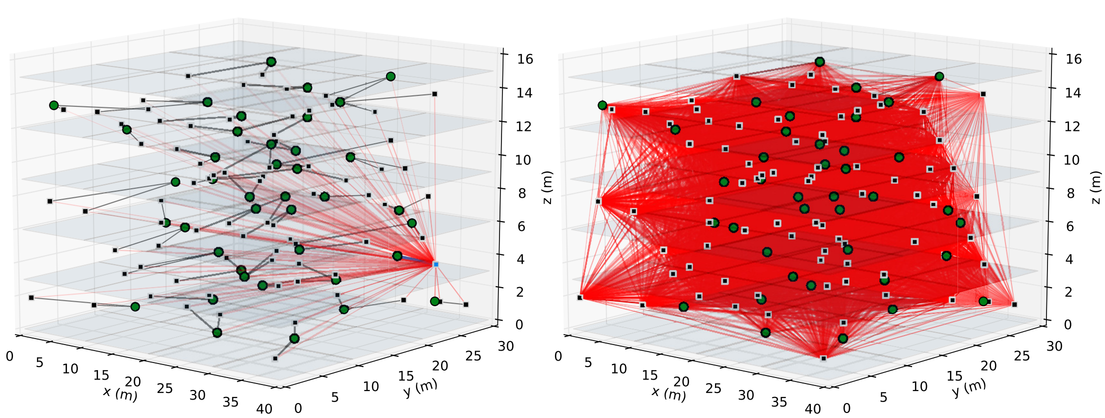


Fig. 4 Projections of a scenario with $\eta = 2$.



(a) (b)

Fig. 5 Graph representation including interferences in a scenario with $\eta = 2$.

($\mathscr{S}$) and Ψ, that models the transmit and success probability of APs and STAs.

To be easily reusable, one of the design requirements is to avoid very specific programming languages or libraries. To this end, our model relies on Python and the widely used *NetworkX* library. Although the model can be extended, our experiments are conducted iusing 20 MHz channels in the most congested 2.4 GHz frequency band. Moreover, we have assumed that STAs attach to their corresponding AP, which is the typical situation in residential environments. Another choice could

Table 3 Summary of parameters.

Parameter	Value
P_t	30 mW
G_t	0 dB
G_r	0 dB
$\mathscr{S}$	−85 dBm
Ψ_{AP}	0.5
Ψ_{STA}	0.1

have been that each STA associates with the AP with the highest SINR, which is the usual situation in enterprise environments, where there are several APs for a single Wi-Fi network.

5.1. Validation of the model

To validate the model we have chosen a simple experiment, evaluating how the throughput and SINR change when a STA moves away from its associated AP. For this purpose, and to avoid any other effect, we have used a very simple graph that consists of a single AP with a single STA, so there are not interferences and we can focus in how the throughput changes with the distance. Additionally, we use this setting to validate the proposed model running the same experiment also with a well-known discrete event simulator: ns-3 [41]. Note that to be able to compare both proposals, we have used in ns-3 the same indoor propagation model as in our model: ITU-R P.1238–10. Moreover, we have setup the Wi-Fi manager in the simulator according to the settings used in our experiments. Finally, and regarding the traffic load of the different network elements, as our model computes the highest reachable throughput that STAs can obtain, in the simulator we have considered greedy traffic sources emitting UDP datagrams with a rate higher than the maximum throughput that can be obtained by Wi-Fi networks.

Fig. 6 shows how SINR and throughput change when the horizontal distance (in the same floor) between AP and STA changes, both using our model and the discrete event simulator. First of all, we can notice that the SINR obtained by our model and the simulator completely coincide. However, when we inspect the throughput, we note an offset between both models. The reason of this offset is because ns-3 measures the throughput at the application layer (usually called goodput) and our model measures it at the physical layer. Therefore, the difference between both curves is due to the overhead introduced by the different protocols operating in the different layers of the protocol stack, so we can conclude that our model, in comparison to a well-known discrete event similator, is valid.

We now inspect the shapes of the curves themselves, as we have chosen a simple setting also to check if the behavior of the model matches the theoretical expectations. We can see that SINR exponentially decays when the STA moves away from the AP. Moreover, when the STA is 16 meters away from the AP there is an abrupt decay because of the propagation model used, which changes the power loss coefficient N at that distance (see Eq. 1). However, we can see that this discontinuity in SINR computation has no effect on throughput computation, since the STA is able to get the maximum available throughput (65 Mbps using MCS 7) until it is 18.4 meters away from the AP. Further from this point, it cannot use MCS 7 anymore and uses MCS 6 instead, decreasing the throughput down to 58.5 Mbps. A similar behavior can be observed when the distance is 22.62, 26.96, and 36.07 meters, as the MCS used changes to MCS 5, MCS 4, and MCS 3, obtaining 52, 39, and 26 Mbps, respectively. However, when the distance is 38.32 meters, there is an abrupt decay in throughput, that equals to zero from that distance on. The reason for this decay is that the power of received signal at the STA is lower than the sensitivity of the receiver ($\mathscr{S} = -85$ dBm), so it cannot be decoded. Note that in this case the sensitivity is limiting the use of MCS 2 to MCS 0. However, this does not mean that these MCS indices will not be used in any case, because there can be situations when the received signal is higher than $\mathscr{S}$ but, due to undesired interferences, SINR is in the range of those MCS indexes.

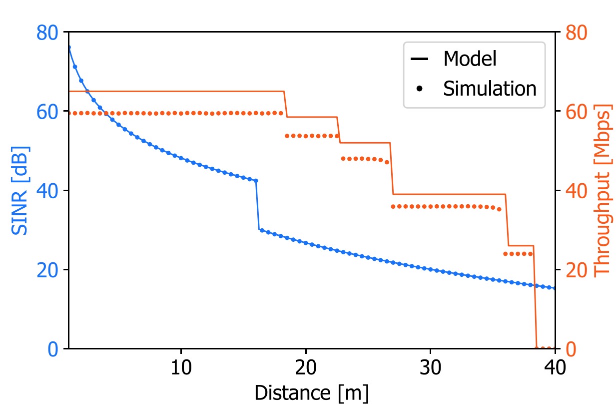


Fig. 6 Effect of the horizontal distance between AP and STA in throughput and SINR.

5.2. Effect of vertical distance in throughput and SINR

After evaluating the impact on performance due to a horizontal movement of the STA, we can now analyze, in the same setting as in the previous section, the impact of moving the STA vertically, i.e., across different floors, so we can show the impact on performance of traversing different floors. To perform this experiment, we have situated the AP at ground level and moved the STA vertically, starting from the same position of the AP. Following this movement, the STA will change the floor every 3 meters, provided that this is the height of each floor. Fig. 7 shows the results of such vertical movement. We have used green dashed vertical lines to represent when the STA goes up to the next floor. As we move the first 3 meters, the behavior is the same as in the horizontal movement, as we are moving inside the first floor. Regarding the obtained SINR, when $d = 3$ meters we notice the first 10 dB decay in the SINR due to the effect of losses across adjacent floors. This behavior is repeated every time that the STA goes up a floor. Moreover, there is another abrupt decay at $d = 16$ meters, because of the change of the power loss coefficient from $N = 28$ to $N = 38$ (which again does not affect throughput computation). If we analyze the achieved throughput, we notice that it is possible to use MCS 7 (and therefore the max-

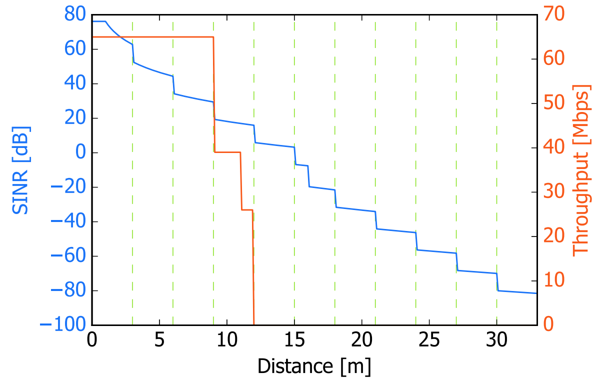


Fig. 7 Effect of the vertical distance between AP and STA in throughput and SINR. Green dashed vertical lines represent a change of floor.

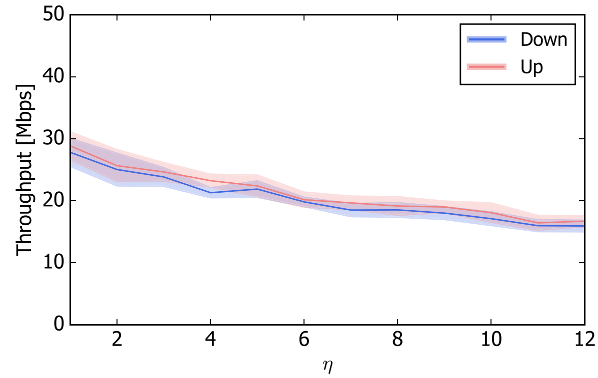


Fig. 8 Effect of the density in throughput.

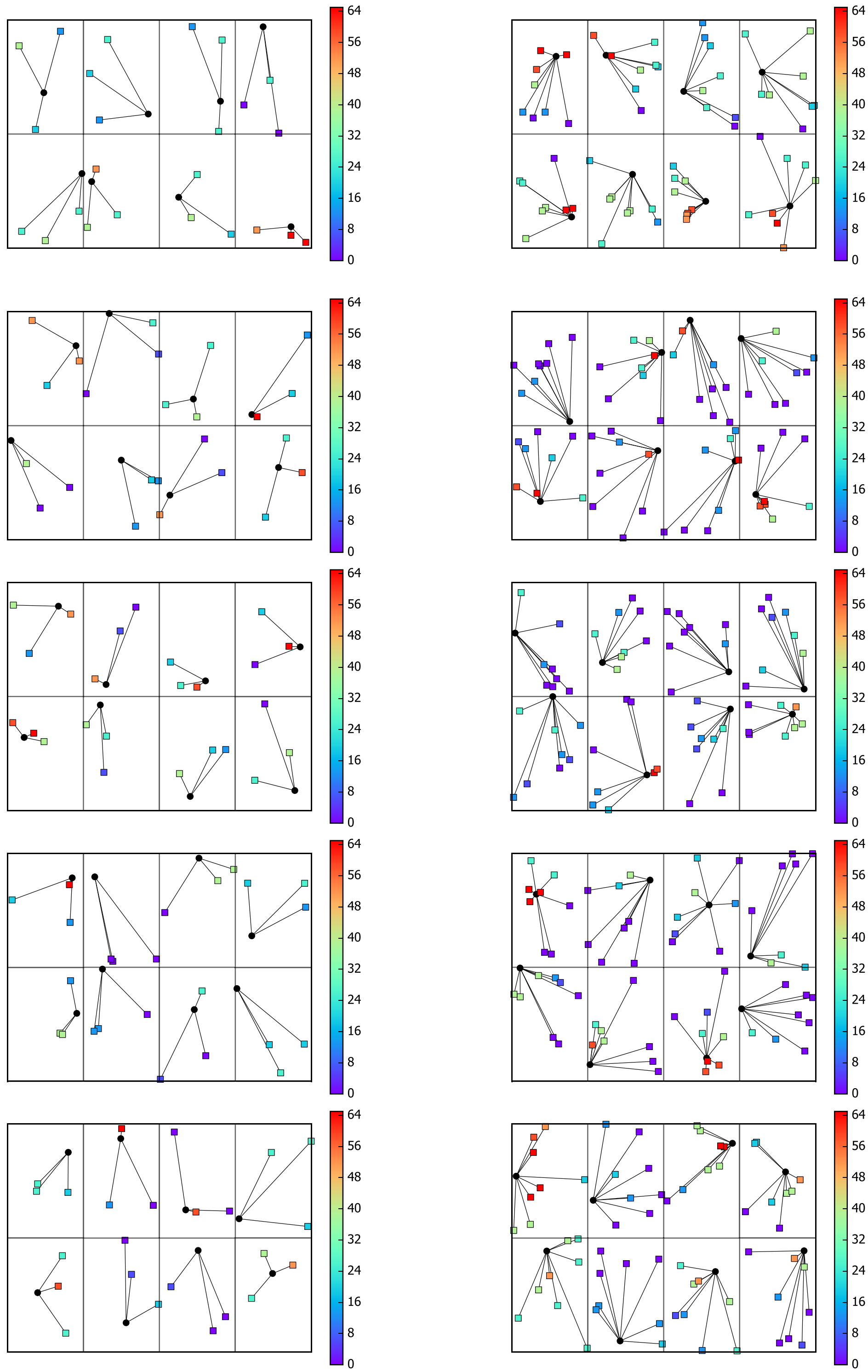
imum throughput) even in the third floor. However, there is an abrupt decay in the throughput in the fourth floor, as we use MCS 4 when the STA is close to the floor and MCS 3 in positions of the fourth floor close to the ceiling. Finally, the received signal is below the sensitivity when we are in the fifth floor, so the STA cannot keep connected and the obtained throughput is zero. At this point, it is important to remember that this behavior is a maximum performance bound of the signal quality that could be obtained when we move across different floors, as in this experiment we are not considering other Wi-Fi devices that cause harmful interferences. Finally, if we compare Figs. 6 and 7, we notice that, as expected, the signal quality degrades much faster when we move vertically than it did when moving horizontally.

5.3. *Effect of the density of STAs*

Now, we evaluate the proposed model in terms of the throughput achieved when the density of STAs changes. For this evaluation we make use of the three-dimensional 5-floor building graph described in Section 4.2. In this model, there is a parameter, named η, that describes the number of STAs associated to each AP in the graph. This parameter ranges from $\eta = 1$ (there is a STA associated to each AP), until $\eta = 12$ (with 12 STAs per AP), so it yields experimental settings with a wide diversity of STA density.

However, before using the graph model to compute the throughput in this setting, we have to define how the different APs are configured in terms of which Wi-Fi channel they are using, since now we have to take into account the effect of interferences, and these vary greatly depending on channel assignments. Although there have been many specific proposals to assign channels to the different APs in Wi-Fi networks [2,24,10,42,43], in order to make the model as general as possible, we use a generic procedure inspired in [44], which is also the *de facto* standard in commercial, residential access points. This procedure is widely used and consists of each AP scanning the spectrum and using the frequency channel where it finds the least interfering power coming from other signals. Once we have assigned channels to all APs in the setting using this approach, we have computed the average uplink and downlink throughput for the 10 different scenarios we have for each value of η. In Fig. 8 we show the mean and 95% confidence intervals for both uplink and downlink throughput for different values of the density η. We can see that there are not statistically significant differences between the uplink and downlink throughput values. Also, as expected, we notice that the throughput decreases as the density of the layout increases, due to the fact that there are more interferences in settings with higher densities.

Although we have evaluated the average throughput depending on the density of STAs η, in the following we are performing a more in-depth evaluation to gain insight on how a particular density value η affects the throughput achieved by specific STAs. For the sake of space, we limit the presentation of results to two specific layouts with different values of η, namely $\eta = 3$ and $\eta = 8$. Moreover, as the conclusions are equivalent for both uplink and downlink throughput, we only show the results for downlink traffic. Fig. 9 shows the downlink throughput obtained by each STA when $\eta = 3$ (Fig. 9a) and and $\eta = 8$ (Fig. 9b). For each deployment, the figure shows the 5 different floors vertically, so the lower figure represents the first floor, while the upper figure represents the fifth floor. In each floor we also show the 8 different apartments in a 4×2 arrangement. Moreover, it is important to highlight that the layout has been represented with five layers (representing each layer a floor), but the position in the z-axis of each vertex in the graph is a continuous parameter. For the sake of clarity in the representation, we have projected all the STAs and APs in a floor to a plane. However, two Wi-Fi elements can be very close in the z-axis even when they are in different floors, which must be taken into account before interpreting the results, since discretization of the continuous range of heights implies that vertical distance information is partially lost (a single floor represents a whole range in the z-axis position). As expected, to achieve a high throughput, the distance from the AP to the STA plays a paramount role. Moreover, we notice low or even zero throughputs for STAs that are far from the AP, specially if there are many devices from other clusters in another apartment (of the same floor, but also from adjacent floors). We can also see that, in the high-density scenario, floors other than the first and fifth ones have significantly more STAs with the lowest values of throughput, and the middle floor is the one showing less STAs with the highest values of throughput. This is consistent with the expectations, since the center floor is the one which has higher interference from other floors. As expected, first and fifth floors have, on average, better throughput.



(a) $\eta = 3$. (b) $\eta = 8$.

Fig. 9 Downlink throughput (in Mbps) in each STA. From down to top, floors 1 to 5.

5.4. Effect of the co-channel interference

The partial overlap between the frequency channels where Wi-Fi can operate is the main peculiarity of Wi-Fi networks operating in the 2.4 GHz band. As this particularity does not appear in other communication networks, the co-channel interference is not usually considered in models, specially those models used by discrete event simulators. In this section, we compare the throughput that is obtained when we consider the co-channel interference (as our model does) with the performance when we consider that Wi-Fi channels are not overlapped, to evaluate whether the effect of co-channel interference is negligible or not. Fig. 10 shows this effect, proving that the effect of the co-channel interference in the throughput is significant. When we do not consider co-channel interference (i.e., only devices using the same channel are assumed as undesired signals) interferences are much lower and thus the obtained throughput is much higher, but this does not represent the real behavior of Wi-Fi networks, where devices operating in "close" channels actually do interfere. In summary, co-channel interference has a significant impact on performance, so it is a crucial issue to include in a realistic Wi-Fi model.

5.5. Effect of using a three-dimensional layout

In the literature related to research in Wi-Fi networks it is usual to consider planar scenarios. However, in some scenarios, like residential ones, the use of three-dimensional (3D) settings should be considered. In this section we evaluate the importance of considering 3D-layouts instead of the classical 2D ones. For that purpose, we have evaluated the average and 95% confidence intervals of the downlink and uplink throughput for different values of STA density η. More specifically, to study the throughput avoiding the z-axis we have ignored the interferences that are produced across different floors, so the interferences will have their origin in other devices from the same floor. Fig. 11 shows the results of our study. We can conclude that the effect of interferences received from other floors is significant enough to deserve consideration. For that reason, the use of planar layouts to model Wi-Fi deployments in multi-floor scenarios like buildings is not recommendable.

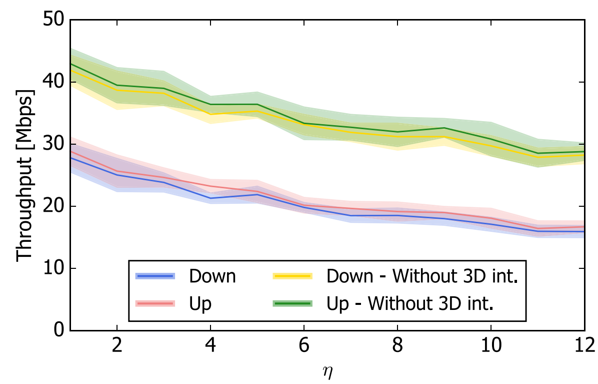


Fig. 11 Effect of using a three-dimensional layout.

5.6. Effect of the propagation model

In this section we evaluate the importance of using different propagation models. In our proposal, we have chosen the indoor transmission loss model defined by ITU-R in the Recommendation P.1238–10 [33]. Obviously, if the setting is a building it is reasonable to use an indoor propagation model. However, as free space propagation models are very widely used, we want to explore whether there are differences in performance when using this type of models instead of an indoor one. As a free space propagation model, we have used the proposal made in [45], because it considers Wi-Fi in the 2.4 GHz frequency band for free space path loss with line-of-sight (LOS) links with antennas between 1 and 2.5 meters in height, as the height of antennas has an impact in the range where the Fresnel zone contacts the ground plane. The propagation model described in [45] for the 2.4 GHz band is:

$$L_{total} = 7.6 + 40\log_{10}d - 20\log_{10}h_t h_r, \qquad (6)$$

being h_t and h_r the height of the transmitting and receiving antennas, respectively. To configure h_t and h_r we have considered them to be 1.5 meters.

Fig. 12 shows the effect of using a free space LOS propagation model instead of the indoor propagation model used in this proposal. We can notice that results significantly differ in both cases. In fact, the throughput achieved when using the free space model propagation is much lower than the throughput obtained in the indoor model. Although losses are higher in the indoor model, it is interesting to note that losses affect not only the desired signal but also the harmful interferences. For that reason, in the free space propagation model the desired signal will be received with higher power, but also the interferences will be higher. Results show that this last behavior prevails over the desired signal, as the final throughput is worse in the free space propagation model.

5.7. Adaptability of the model to other Wi-Fi settings: channel bonding in the 5 GHz frequency band

The experiments shown so far are focused in testing the validity of the proposed model in a well-known and widely studied

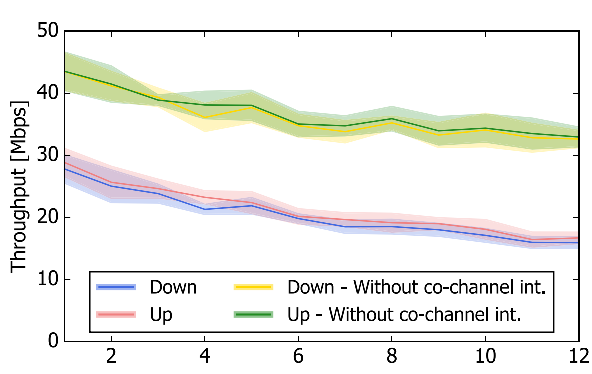


Fig. 10 Effect of the co-channel interference.

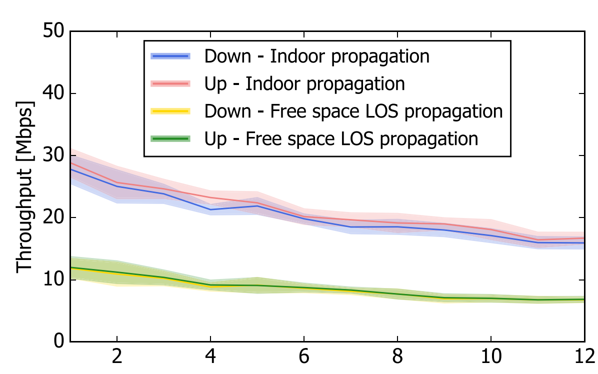


Fig. 12 Effect of using free space LOS propagation model.

Wi-Fi setting (IEEE 802.11n with 20 MHz channels in the 2.4 GHz band). However, one of the key strengths of the model is its adaptability to newer Wi-Fi standards. In this section, we explain how we can easily adapt the proposal to model another paradigmatic example of Wi-Fi setting: the IEEE 802.11ac standard (Wi-Fi 5) using channel bonding in the 5 GHz frequency band. In this setting, the standard allows to use four different bandwidths: 20, 40, 80 and 160 MHz. To adapt the previously used model to this setting we must follow the next steps:

1. *Propagation model*. As the frequency band changes from 2.4 GHz to 5 GHz, the propagation model must be changed accordingly. This change can be easily performed by changing the value of f in Eq. 1. Moreover, as it is stated in the ITU-R Recommendation P.1238–10 [33], losses between adjacent floors are higher in the 5 GHz band. For that reason, in the 5 GHz band we use $L_f(n) = 13n$ dB instead of $L_f(n) = 10n$ dB that we used in the 2.4 GHz frequency band.
2. *Modulation, coding and throughput*. IEEE 802.11ac standard defines a new set of MCS with a certain throughput for each one. As discussed above, we will be able to select a certain MCS level as a function of the experienced SINR. In Table 4 we show the different MCS that can be selected in IEEE 802.11ac when a GI of 800 ns is used. Table 4 also shows the throughput obtained for each MCS and the required SINR thresholds for each MCS, according to [46].
3. *Number of channels and thermal noise*. In addition to the channel width, we also need to specify the number of available channels. Of course, the number of available channels strongly depends on the channel width, i.e. on the way channel bonding is performed. As the channelization for Wi-Fi networks in the 5 GHz frequency varies with the world region, we have chosen the one used in USA. In that channelization the channels are orthogonal and we can use up to 25 channels of 20 MHz width, up to 12 channels of 40 MHz, up to 6 channels of 80 MHz or up to 2 channels of 160 MHz (after adding channel 144 in year 2014 to the original 802.11ac specification). Finally, and depending on the channel width chosen, we must configure thermal noise according to Eq. 5.

With the model adapted to IEEE 802.11ac, as described above, we have evaluated the average throughput obtained by STAs under different types of channel bonding schemes, ranging from not using channel bonding (i.e. with 20 MHz channels) to the use of 160 MHz channels, which are the widest possible channels available in IEEE 802.11ac. Moreover, we focus on the 5 GHz frequency band. Finally, although we have evaluated both upstream and downstream throughputs, we only show results for the downlink in Fig. 13, as the conclusions for both are the same. Results show that the best choice in the evaluated setting for all the values of STA density (η) is to use 80 MHz channels, as it is the best trade-off between bandwidth and number of channels. In fact, 80 MHz channels are probably the most widely used in the 5 GHz frequency band. On the other hand, although 160 MHz channels would allow for higher throughputs, the lower number of available channels increases the interferences as we must reuse them very frequently and in closer places, so the experienced throughput is lower. It is also interesting to highlight the slope of the 40 MHz and, specially, 20 MHz curves, because, under these settings, there are enough orthogonal channels to avoid the use of interfering channels in close APs.

5.8. Effect of external interferences: the Bluetooth case

Another interesting setting where our proposed model can be extended and be easily used is the consideration of external interferences that affect Wi-Fi receptions. This phenomenon occurs as IEEE 802.11 networks operate in unlicensed frequency bands. And this behavior can become especially noticeable in the 2.4 GHz frequency band, where several technologies coexist. Although other interference sources are also possible, a prominent and interesting case is the presence of Bluetooth communications close to Wi-Fi devices that can affect their performance. In this section we have extended our model to include external interferences due to close Bluetooth devices. More concretely, we study how Wi-Fi performance changes when there is a Bluetooth device transmitting at a certain distance from a STA. However, as the diversity of Bluetooth devices in terms of transmission power is very high, we must take into consideration the different power classes of Bluetooth devices, as specified in Table 5 [47]. Moreover, due to the frequency hopping operation of Bluetooth,

Table 4 Relation between MCS, SINR and throughput in Wi-Fi 5 with 800 ns GI.

MCS	Mod. scheme	Coding rate	20 MHz		40 MHz		80 MHz		160 MHz	
			Thr. (Mbit/s)	SINR (dB)	Thr. (Mbit/s)	SINR (dB)	Thr. (Mbit/s)	SINR (dB)	Thr. (Mbit/s)	SINR (dB)
0	BPSK	1/2	6.5	[2,5)	13.5	[5,8)	29.3	[8,11)	58.5	[11,14)
1	QPSK	1/2	13	[5,9)	27	[8,12)	58.5	[11,15)	117	[14,18)
2	QPSK	3/4	19.5	[9,11)	40.5	[12,14)	87.8	[15,17)	175.5	[18,21)
3	16-QAM	1/2	26	[11,15)	54	[14,18)	117	[17,21)	234	[21,24)
4	16-QAM	3/4	39	[15,18)	81	[18,21)	175.5	[21,24)	351	[24,27)
5	64-QAM	2/3	52	[18,20)	108	[21,23)	234	[24,26)	468	[27,29)
6	64-QAM	3/4	58.5	[20,25)	121.5	[23,28)	263.3	[26,31)	526.5	[29,34)
7	64-QAM	5/6	65	[25,29)	135	[28,32)	292.5	[31,35)	585	[34,38)
8	256-QAM	3/4	78	$\geqslant 29$	162	[32,34)	351	[35,37)	702	[38,40)
9	256-QAM	5/6	-	-	180	$\geqslant 34$	390	$\geqslant 37$	780	$\geqslant 40$

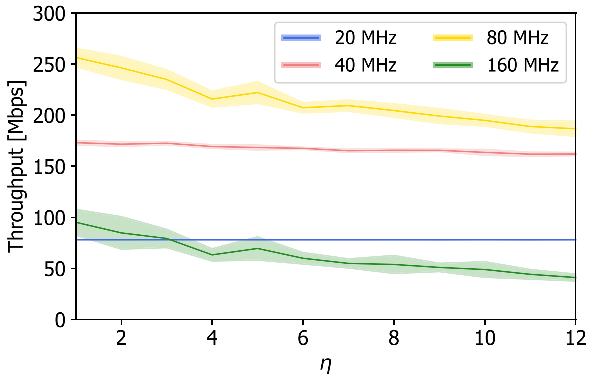


Fig. 13 Effect of channel bonding in IEEE 802.11ac operating in the 5 GHz frequency band.

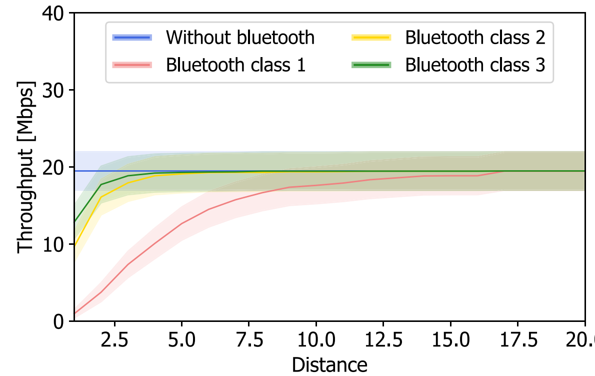


Fig. 14 Effect of Bluetooth interferences in IEEE 802.11.

Bluetooth signals will not interfere IEEE 802.11 signals continuously. Frequency hops occur at a standard hop rate of 1600 hops per second following a pseudo-random sequence, hopping through up to 79 channels (although this quantity can be lower when using Adaptive Frequency Hopping), having each of those channels a bandwidth equal to 1 MHz. To model this pseudo-random behavior of Bluetooth we have averaged the amount of time that a Bluetooth transmission collides with the spectrum used in Wi-Fi. Thus, a Bluetooth communication will collide with a 20 MHz Wi-Fi channel in 20 hops every 79 hops on average, so a Bluetooth communication will interfere with a 20 MHz Wi-Fi channel approximately $20/79 = 25.32\%$ of the time. Moreover, it is also remarkable that a Bluetooth interference does not affect the whole spectrum of a Wi-Fi channel, but only 1 MHz from the total bandwidth of the IEEE 802.11 channel.

Next, we conduct some experiments to show the proposed model capability of considering external interferences into Wi-Fi communications. The main results of this study are shown in Fig. 14, where we show, for a scenario with 6 STAs per AP, how the downlink throughput of STAs is affected when a Bluetooth device is transmitting at a certain distance. As the different transmission power classes are defined in terms of a transmission power interval, we have used the worst case for all of them in terms of interferences. Taking this into account, we have used the highest power for each interval (100 mW for class 1, 2.5 mW for class 2 and 1 mW for class 3). In Fig. 14 we can see that, as expected, when Bluetooth transmitting devices are closer to the Wi-Fi STAs, throughput can be severely affected, especially with the highest power Bluetooth class. And, as Bluetooth interfering devices are further, their effect quickly dispels. Moreover, it is important to highlight that, as expected due to its low transmission power, the effect of class 2 and class 3 Bluetooth devices in Wi-Fi communications can only be noticed at very short distances.

Table 5 Power transmission classes defined in Bluetooth [47].

Power class	Power (in mW)	Power (in dBm)
1	(2.5, 100]	(+4, +20]
2	(1, 2.5]	(0, +4]
3	⩽1	⩽0

6. Conclusions and future work

One of the main problems in Wi-Fi network planning and optimization research is the difficulty to compare approaches from different authors, due to the vast diversity of models considered by the different research groups working in this area. The present paper bridges this gap presenting a generic model for signal propagation, goodness computation, and scenario representation in Wi-Fi infrastructure networks, which is flexible and easily reusable by the community. First, we provide a realistic model to represent Wi-Fi settings, including architecture, signal propagation, and interference and throughput computation. Then, we propose a compact graph-based scenario representation and a collection of realistic scenario settings representing residential buildings with several floors (hence three-dimensional scenarios), with varying density of wireless devices (for a total of 120 scenarios). Finally, we have conducted a comprehensive set of validation experiments including a comparison with the well-known discrete event simulator *ns-3*. Results show the consistency of the model and the relevance of some of its design features, like the use of 3-D graphs and the consideration of co-channel interference.

For validation, our proposed model has been particularized for a specific kind of realistic Wi-Fi network deployments. More specifically, the design requirements of the model have been driven by the features of dense and ultra-dense Wi-Fi networks operating in the 2.4 GHz band, as these types of networks are usually the ones that require a more accurate design and optimization to prevent clients from obtaining a very poor quality of service.

For the experimental evaluation of the model, we have made a number of assumptions. We have restricted ourselves to the 2.4 GHz band, indoor residential propagation, and specific co-channel interference values [38]. We have also assumed that clients associate to the access point of their same residential unit. We believe these assumptions to be reasonable and realistic. In any case, the model is flexible enough to support other bands, propagation parameters, and interference assumptions. We believe this model adequately fills the gap for the comparison of different proposals in the earlier and middle stages of research, before fine-tuning with discrete-event simulations.

We believe the two main strengths of our proposal are its realism and adaptability. By taking into account STA density, co-channel interference, 3D wireless settings and indoor propagation, the model allows to accurately represent practical realistic scenarios, so that researchers can use it to refine their approaches before carrying out more computation- and time-expensive simulations. Also, as we have shown in the last sections of the paper, the model can be easily adapted to incorporate other technologies or modifications over the existing ones, which allows for an agile exploration of the design space when researching on new methods to improve the efficiency of our exploitation of the wireless spectrum. We envision our model being used for rapid prototyping of new features in wireless controllers, access points and STAs, and even of new protocol extensions and updates [48].

Though the experiments performed with the model and the graphs generated yield satisfactory results, there is still plenty of research to be done in this area. First of all, our model is static, so right now to work with highly changing environments users will need to either abstract that dynamicity (e.g. taking averages) or to work with time "slices" where the properties of the scenario are stationary enough. One of our immediate avenues for future research is to consider dynamic scenarios. In addition, we are interested in exploring different graph generation strategies, not only to account for different building shapes, but also to widen the diversity of the topological properties of the scenario graph, thus enabling studies about how graph metrics impact the relative performance of different coordination approaches, similar to the ones we conducted in [32]. We are also interested in generating the most usual scenarios in the literature and in performing an exhaustive comparison of the most relevant works in those scenarios. Finally, we plan to integrate the model and the analysis code (right now available as supplementary material for this article) in a web service, which will allow to share scenarios and experiment results with the Wi-Fi planning and optimization community more easily, further facilitating in this way that researchers compare and share their advancements.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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Appendix A. Supplementary materials

Our aim is for the proposed model to be useful to the research community to evaluate and validate their approaches for Wi-Fi network planning, coordination, and optimization. In a sense, we are trying to provide the model we would gift our "past-selves" seven years ago to avoid a number of headaches and bottlenecks. It is our hope that readers can benefit of this model to facilitate their research progress in this fascinating and promising area.

The graph files and the corresponding EPS figures can be downloaded from https://doi.org/10.5281/zenodo.5703320. The code (in Python) we have used to evaluate throughput in a given setting is available upon request. All the material is licensed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/), which means that you can use it and adapt it as long as you cite this paper as its original source, which we would of course greatly appreciate.

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