Random Access in IRS-assisted 802.11 Networks

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***Abstract*—Most works on intelligent reconfigurable surface (IRS)-assisted networks consider link-level simulations and do not address the upper protocol layers. This limitation becomes particularly relevant in practical systems like 802.11 Wi-Fi, where channel access is based on listen-before-talk (LBT) scheme, making conventional IRS scheduling strategies (time-division or centralized coordination) difficult to apply. Given these reasons, we shift the focus to random channel access based on carrier sense multiple access with collision avoidance (CSMA/CA) to explore how an IRS can be beneficial in such scenarios. We first discover that improving the SNR of links from stations (STAs) to an access point (AP) introduces the potential risk of hidden terminals among the STAs in the uplink. To analyze this, we introduce `ns3IRS`, a framework that integrates a model of an IRS into the ns-3 network simulator, which allows us to run the full Wi-Fi stack within an IRS-assisted wireless network. We propose two solutions to mitigate the hidden terminal problem caused by the IRS also by assuring mutual carrier sensing: (i) splitting a single centralized IRS, or (ii) using additional small IRSs nearby the STAs – to create direct links among them, with the purpose of enabling mutual carrier sensing. Results show that these two solutions can improve the throughput compared to the traditional approach where virtual carrier sensing, i.e., CSMA/CA with Request-to-Send/Clear-to-Send (RTS/CTS), is used. For instance, for a system with four users, the proposed approaches improve the throughput from 25 Mbit/s to around 35 Mbit/s compared to the baseline scenario with RTS/CTS. Additionally, latency and jitter are decreased. However, as the number of users increases, achieving performance gains requires a larger IRS, since the gain scales with the number of reflecting elements, especially for the centralized IRS. In scenarios where scaling the IRS is impractical, CSMA/CA with RTS/CTS may become a more effective alternative.**

***Index Terms*—Intelligent Reconfigurable Surfaces, ns-3, WiFi, Cross-layer, Hidden Terminal Problem, Random Access, IRS, RIS**

I. Introduction

Ensuring reliable wireless communication is critical under non-line-of-sight (NLOS) conditions. A promising solution to that is the use of intelligent reconfigurable surfaces (IRSs) for enabling a smart radio environment (SRE) [1]. An IRS usually consists of many reconfigurable tiny antenna elements to allow precise control of signal reflection and scattering, optimizing signal strength, coverage, and interference management [2].

Due to the potential of an IRS to illuminate "dark areas" and establish communication in the absence of direct line-of-sight (LOS), there is growing interest in further exploring this technology for next-generation communications [3]. For that, it has to be investigated how an IRS should be configured and shared between multiple users. However, most existing works that address multi-user IRS-assisted scenarios either focus on optimizing a single reflected beam (see [4]), or rely on a scheduled channel access, e.g., time-division, where the IRS configuration is periodically switched to serve different users [5]. These approaches often assume idealized and coordinated settings, which may not hold in practice. The configuration overhead and user scheduling in IRS-assisted networks actually add another layer of complexity compared to traditional systems [6]. In particular, Wi-Fi uses a random channel access through carrier sense multiple access with collision avoidance (CSMA/CA), which makes predictions of which station (STA) will send at which point in time nearly impossible. Therefore, configuring an IRS such that it strengthens the link from the STA which is sending next to the access point (AP) is difficult. That is why in this paper, the IRS is configured to support all links from the STAs to the AP in parallel, without the need for reconfiguration. A reconfiguration is needed only when a STA leaves or joins the network.

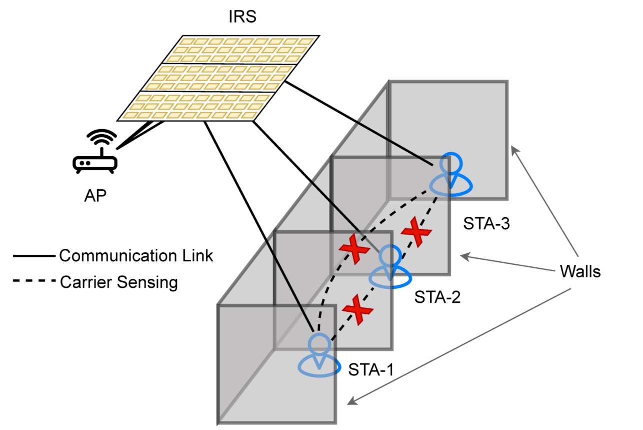


Figure 1: An IRS is used to enable/improve the communication links between the AP and the STAs. Here a single IRS is split into multiple tiles so that each tile is optimized for a particular AP-STA link. This may lead to the creation of hidden terminals.

A well-known problem of CSMA/CA is the possibility of the existence of hidden terminals. They occur when wireless nodes, e.g., STAs, are unable to sense each other's transmissions, leading to concurrent uplink transmissions and hence packet collisions at the AP, resulting in inefficient channel use. Note that hidden terminals can also occur between neighboring APs (overlapping BSS) in the downlink. Even in Wi-Fi 6 and above, where OFDMA prevents hidden terminals within a cell, IRS configuration is still difficult, due to its frequency-agnostic nature [7]. Additionally, hidden terminals in this case can occur between overlapping cells, where no explicit coordination is implemented. With the introduction of antenna beamforming, hidden terminals are created artificially. This is also known as hidden beam problem [8]. In more detail, in systems where beamforming is used, such as with directional antennas, a signal is typically focused in a particular direction towards a desired receiver. However, this focusing of the signal towards one direction decreases the power of the signal in other directions, which causes STAs to be unaware of the ongoing transmission. This circumstance can lead to interference if the other STAs start a transmission simultaneously. The result is a decrease of the system's performance.

Our study in this paper shows that the same problem might occur when an IRS is used, since it also performs passive beamforming. Consider the office environment as illustrated in Figure 1, which consists of multiple rooms divided by walls in between, and they have an open ceiling, where an IRS is installed. In the simplest approach, the IRS is split statically and optimized for all the users in the different rooms to enable an improved link towards the AP. However, due to the hidden beam problem and the walls in between, the STAs do not sense each other. As a countermeasure, we propose two different IRS incorporation strategies, showing that IRS can indeed resolve the hidden terminals it creates. We propose splitting the IRS into even more tiles and optimize each tile to enable mutual carrier sensing, such that also inter-STAs links improve. Additionally, we propose the usage of additional small distributed IRSs near the STAs and optimize them to create links between the STAs, while the central IRS still improves the links from the STAs to the AP. Traditionally, Wi-Fi is using virtual carrier sensing, i.e., CSMA/CA with Request-to-Send/Clear-to-Send (RTS/CTS), to resolve hidden terminals, however, this comes with the cost of communication overhead due to the transmission of the RTS/CTS control frames at base rate. Thus, IRS may be an alternative solution that does not introduce similar overhead. However, our approaches come with costs for the deployment of the IRSs, parts of which are used to strengthen the links between the STAs and are not available for boosting the communication towards the AP anymore. To the best of our knowledge, this is the first work dealing with hidden terminals with IRS so far.

Given that physical IRSs are still rare and expensive to deploy at scale, the vast majority of research relies on simulations. To date, most of these simulators focus predominantly on the link-level, leaving a significant gap in understanding how an IRS would impact higher-layer protocols and overall network behavior—particularly with respect to metrics such as latency, throughput, and packet loss. Issues like the hidden terminal problem are captured when both PHY and media access control (MAC) layers are modeled, which is not the case in link-level simulations. Combining all the aforementioned reasons, in this work we present `ns3IRS`, which allows seamless integration of IRS into the ns-3 network simulator that can be applied to a wide range of wireless technologies, such as Wi-Fi and LTE. Using `ns3IRS`, we show that while strengthening the link from the STAs to the AP – which is one of the main applications of IRS – hidden terminals may be created, which decrease the overall throughput in a multi-user network.

The main contributions of this paper are:

- We introduce `ns3IRS`, a novel extension of the ns-3 simulator that supports IRS nodes,
- Through system-level simulations, we show how usage of an IRS can create hidden terminals when using random access protocols like CSMA/CA,
- We then show how a proper usage of the IRS can also solve these hidden terminals,
- We study the limits of an IRS approach and isolate the cases when classical virtual channel reservation, i.e., CSMA/CA with RTS/CTS, is a useful alternative,
- We show through simulations that IRS enhances multi-user communication in three key directions: it facilitates connectivity, optimizes MAC layer operations, and reduces latency; provided it is carefully integrated into the network.

The rest of the paper is structured as follows. Section II gives an overview on related works, whereas Section III provides the necessary fundamentals for this paper. Next, the implementation of `ns3IRS` is given in Section IV. The discussed problem is introduced in Section V, and the proposed solution in Section VI. Evaluation and results are presented in Section VII, followed by the discussions in Section VIII.

II. Related Work

Given the cost of experimental studies with IRS and its rare availability, simulations are a key in IRS research. Several works discussing a proper channel model for IRS have been published to this end. [9] define new path loss models for IRS based on physical optics techniques. A model based on experimental study in [10] reveals that the dimension and the configuration of the IRS and its distance to the transmitter (Tx) and the receiver (Rx) plays an important role in its performance. However, this work is limited to a single antenna system and does not take the direct link between Tx and Rx into account. To address some of these limitations, an improved path loss model that considers practical electromagnetic effects is proposed in [11] and validated on a 24×24 cross-dipole-shaped unit cells operating at 29 GHz.

Additionally, there are several works on simulation tools for IRS. The open-source *SimRIS Channel Simulator* MATLAB package, introduced in [12]–[14], supports physical layer simulations of IRS-based communication systems. It allows to simulate a static setup with adjustable operating frequency, terminal and IRS locations, the number of IRS elements, environmental settings and multiple input multiple output (MIMO). The simulator is primarily designed for millimeter wave (mmWave) frequencies, specifically 28 GHz and 73 GHz, and does not support lower frequency bands commonly used in sub-6 GHz wireless communication systems such as Wi-Fi.

The open-source simulation platform QRIS [15], built on the QUAsi Deterministic Radio channel Generator, enables the simulation of wireless networks with multiple IRS and endpoint devices across various scenarios, including indoor Wi-Fi and 5G networks. Similarly, the Vienna Stochastic Link

Simulator by incorporating a MATLAB ray tracer to enhance path loss modeling for IRS is extended in [16]. IRS can also be included in the Sionna Ray Tracing module, where the IRS node is modeled via a phase and amplitude profile that together define the reradiated electromagnetic field [17].

However, all the presented works focus solely on the simulation of IRS at the link level, rather than the system level. Studying the impact on the higher network layers is essential for assessing how IRS impacts the overall performance in practical deployments, including latency, throughput, and packet loss. Factors such as interference management or dynamic adaptation of network resources to changing environments (e.g., mobility, varying traffic loads) are critical to real-world applications. However, they are are often missing in purely physical layer models and require the full implementation of the higher layers. Among available tools, the open-source packet-level network simulator ns-3 represents the state of the art for simulating complex network topologies and end-to-end protocol stacks. It supports a wide range of network elements and wireless technologies and provides abstraction of the physical layer to enable scalable and efficient simulation. However, despite its flexibility, ns-3 currently lacks a model for incorporating an IRS, making it difficult to study its system-level and protocol-level implications in realistic multi-user environments.

There is also a shortcoming visible in the literature when it comes to the analysis of IRS in the upper layers. To start with, only a limited number of studies have addressed how IRS-assisted systems perform under random access-based protocols. For example, [18] proposed a distributed CSMA algorithm, where each source-destination pair decides whether to use direct links or probe source-IRS-destination links. [19] presented a MAC framework for uplink multi-user communication, which operates in two distinct phases: a negotiation phase and an IRS-assisted transmission phase. During the negotiation phase, users compete for access according to a backoff mechanism and negotiate with the AP to reserve IRS, power, channel, and time slot resources. In the subsequent transmission phase, the IRS is configured to serve the selected users according to the reserved resources.

The hidden terminal problem has been widely studied in the literature. For instance, a machine learning (ML) model is proposed in [20] to help a IRS in the cognitive ratio to calculate a sufficient number of secondary users without creating hidden terminals. To avoid hidden terminals, [21] introduce an algorithm to find and identify them in a network by exchanging information between the STAs. They base the algorithm on sensing, where they check if a STA can demodulate packets from another STA, or if it can just detect its presence by energy detection. For Wi-Fi 7, [22] propose an algorithm on the dynamic sensitivity control to decrease the number of hidden terminals. [23] propose scaling down the power in a full duplex scenario on both sides in order to reduce the number of hidden terminals.

To the best of our knowledge, no prior work has demonstrated that IRSs can introduce hidden terminal issues, nor has it explored how IRSs themselves can be used to address such issues without having to modify the protocol or rely on virtual channel reservation. Given the absence of upper-layer IRS simulators, a tool like ns-3 is well-suited to provide a comprehensive analysis of the hidden terminal problem in IRS-assisted networks. In this context, we propose configuring the IRS in such a way that the physical carrier sensing remains functional, thereby allowing the use of standard random access mechanisms such as CSMA/CA.

III. BACKGROUND

A. Intelligent Reconfigurable Surfaces

Generally speaking, one can picture an IRS as a thin, inexpensive adaptive composite material sheet, comparable to a wallpaper, which can be applied to surfaces such as walls, windows, or ceilings, thereby transforming ordinary environments into intelligent communication interfaces [1]. Essentially, an IRS functions like a programmable mirror for wireless signals, capable of redirecting, focusing, or modifying radio waves through external electronic control. The key innovation lies in their dynamic reconfigurability, which enables adaptive signal reflection and steering, leading to smarter radio environments that improve coverage, increase capacity, and reduce interference in wireless networks.

The reflection coefficients of an IRS represent the parameters that control how an incoming electromagnetic wave is reflected. Each element on the IRS can adjust its reflection coefficient, typically represented by a complex number [24], to control the phase and amplitude of the reflected signal. In an IRS-assisted single-user system, the received power increases in proportion to the number of reflective elements, N, in the order of N^2. This means that each doubling of the number of elements results in an approximate 6 dB increase in the power gain [25]. IRS offers various applications and benefits. For instance, it can enhance signal strength through constructive interference [26], can mitigate interference [1], and improve energy efficiency in wireless power transfer [27]. Additionally, IRS can increase channel capacity by optimizing the channel matrix rank [1] and enhance radio localization through wavefront curvature and multipath reflections [28].

B. Virtual Channel Reservation

The RTS/CTS mechanism is a MAC protocol for virtual channel reservation and can be used to mitigate the hidden node problem in wireless networks with CSMA/CA. It operates by enabling a sender to reserve the wireless channel before transmitting data, thereby reducing the likelihood of collisions. When a node intends to send data, it first transmits a short Request-to-Send (RTS) frame to the receiver. Upon successful reception, the receiver replies with a Clear-to-Send (CTS) frame, signaling that the channel is clear for communication. Nodes overhearing either the RTS or CTS frame defer their transmissions for the duration of the data exchange, effectively minimizing interference. While RTS/CTS introduces additional overhead, it significantly improves performance in scenarios with high contention or poor channel conditions. The mechanism is particularly relevant in IEEE 802.11 networks and

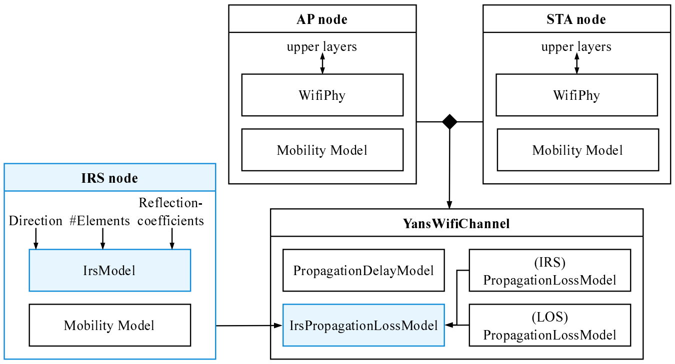


Figure 2: Architecture of `ns3IRS`; we introduce `IRS node` and `IRSPropagationLossModel` classes.

can be enabled adaptively based on frame size or network congestion levels [29].

C. ns-3 Network Simulator

The ns-3 network simulator is a modular, open-source, and event-driven packet-level simulator developed in C++. It is widely adopted in academic and industrial research, which continuously drives the development and integration of new technologies across various layers of the network stack, including protocols such as TCP, UDP, Wi-Fi, LTE, and WiMAX. At the physical layer, ns-3 uses abstract models rather than full waveform-level simulation. It offers several built-in wireless channel models, such as free-space propagation, fading, and NLOS propagation, to represent realistic signal behavior. Simulation in ns-3 is organized around core components like the `Node` class, which acts as a container for different `Applications`, `Protocols`, and `NetworkDevices`. Each `Node` can also be assigned a physical position in the simulation environment. The `NetworkDevice` represents a technology-specific network interface card and is connected to a `Channel` object that handles communication with other devices. ns-3 includes predefined channel models for various technologies, for example, the `YansWiFiChannel` for Wi-Fi simulations and a more flexible `SpectrumChannel` for custom or advanced wireless scenarios. The channel model incorporates physical layer effects through two main components:

- `PropagationLossModel`, which accounts for attenuation due to distance, obstacles, and environmental factors,
- `PropagationDelayModel`, which captures signal propagation delays over the channel.

This modular approach allows ns-3 to simulate complex environments on system-level, including indoor settings with multi-path fading effects and reflections, providing a rich testing ground for wireless communication research [30], [31].

IV. `ns3IRS` in a Nutshell

In this work, we introduce `ns3IRS`, a model of an IRS in ns-3 with a proper abstraction. This enables full-stack simulations of wireless protocols in IRS-assisted scenarios. We made our extension available as open source.[1] We model the IRS within the channel making it independent of technologies and MAC protocols, e.g. `ns3IRS` can also be used for scheduled TDMA approaches. To build the extension, we make two main changes to ns-3, shown in the shaded boxes in Figure 2. We introduce an `IRS node` representing the IRS in ns-3 and storing its position (via a mobility model), its orientation and the configuration of the IRS. Configuration of the IRS can be achieved either through the specification of nodes we want to optimize the IRS for as described in Section IV-B or by manually calculating the reflection coefficients. As long as the configuration of the IRS is not changed, the calculated characteristics of the outgoing signal (gain and phase) are cached to reduce the execution time of simulations. The IRSs are grouped within a `NodeContainer`, enabling compatibility with ns-3 helper functions, like the mobility helper for applying mobility models.

The second change to ns-3 is the introduction of a new propagation loss model. No additional delay from the IRS is added, as it just introduces an additional reflection path to the channel. Our `IRSPropagationLossModel` stores two distinct path loss models by itself, the loss model for the (N)LOS path between transmitter and receiver, and the loss model for the path $Tx \rightarrow IRS$ and $IRS \rightarrow Rx$ or between multiple IRS. The usage of two propagation loss models allows modeling of walls between the transmitter and the receiver while there is LOS for the path towards and from the IRSs. The new `IRSPropagationLossModel` calculates the power at the receiver for the signal received over the different paths. It calculates the loss of each segment of the path and combines it with the gain of the IRS. Additionally, it calculates the delay of each path segment and adds the delay introduced by the phase shift of the IRS to it. This is required, as the different copies of the signal traveling over the different paths may interfere constructively or destructively. Additionally, reflections passing multiple IRS are considered, however, when the signal is too weak, the paths from multiple IRS hops are ignored.

A. IRS Model

The complex transfer function of a path i is described as H_i, capturing both attenuation and phase shift introduced by propagation, given as:

$$H_i = \frac{1}{a} \mathrm{e}^{2\pi \mathrm{i} f \frac{d}{c}}, \tag{1}$$

where, a is the path-loss derived by a channel model and d the distance between the nodes, which creates the phase shift of the signal. This phase shift is calculated based on the signal's frequency f and the speed of light c. The gain of the IRS can be described in a complex representation:

$$G_{\text{IRS}} = \alpha \cdot \mathrm{e}^{\mathrm{i}\Gamma}, \tag{2}$$

where α is the real gain and Γ the phase shift of the IRS caused by the time delay. Both values depend on the signal's angle of incidence and reflection. The power at the Rx (P_{Rx}) depends on the transmitted power (P_{Tx}) and the sum of all

[1] https://github.com/tkn-tub/ns3irs

channel components arriving at the Rx. Therefore, in a simple scenario of two nodes and one IRS, P_{Rx} is calculated as:

$$P_{\text{Rx}} = P_{\text{Tx}} \left| H_{\text{Tx-Rx}} + H_{\text{Tx-IRS}} \cdot G_{\text{IRS}} \cdot H_{\text{IRS-Rx}} \right|^2, \tag{3}$$

where $H_{\text{Tx-Rx}}$ describes the transfer function of the direct path between Tx and Rx, $H_{\text{Tx-IRS}}$ and $H_{\text{IRS-Rx}}$ describe the transfer functions of the components to the IRS and from it and G_{IRS} describes the complex gain of the IRS. `ns3IRS` can also handle multiple IRS, which results in more received components which can also be reflected by multiple IRS after each other. It should be noted that we assume that the transmitter and receiver antennas are omnidirectional. Moreover, since the signal bandwidth is comparable to the coherence bandwidth, we use the narrowband model for the IRS [32].

B. Configuration of the IRS

To calculate the IRS characteristics, we aim to control the phase of the reflected signals from all its elements such that they arrive at the receiver in phase with the direct path signal. The total phase shift ϕ required to achieve this, considering the path length difference, is given by:

$$\phi = \frac{2\pi \left(d_{\text{Tx-IRS}} + d_{\text{IRS-Rx}} - d_{\text{Tx-Rx}} \right)}{\lambda}, \tag{4}$$

which accounts for the phase difference between the reflected path (Tx $\rightarrow$ IRS $\rightarrow$ Rx) and the direct path (Tx $\rightarrow$ Rx), where λ is the wavelength. The reflection coefficients Γ that the IRS must apply to achieve optimal phase alignment are then calculated as:

$$\Gamma = \exp\left(\mathrm{i}\left(\phi - \mathbf{arg}(\mathbf{a}(\theta_{in}, \varphi_{in})) - \mathbf{arg}(\mathbf{a}(\theta_{out}, \varphi_{out}))\right)\right), \tag{5}$$

where $\mathbf{a}(\theta_{in}, \varphi_{in})$ and $\mathbf{a}(\theta_{out}, \varphi_{out})$ are the steering vectors corresponding to the angles of arrival and departure, respectively [33]. The function $\arg(\cdot)$ extracts the phase of each steering vector component, which accounts for the angular response of the IRS. These steering vectors are calculated based on the positions of Tx, Rx, and the IRS. For our calculations, we assume perfect knowledge of the position of the nodes and the IRS and that we can configure any phase shift of the IRS without limitations due to quantization. The maximum gain at the receiver is achieved when the IRS elements are configured to compensate for the phase shifts introduced by the two cascaded links: $Tx \rightarrow IRS$ and $IRS \rightarrow Rx$. In this configuration, the individual contributions of all reflecting elements add up coherently, resulting in constructive interference of the reflected signal at the receiver. However, if the position of any node changes slightly, the path lengths and angles of arrival/departure are altered, leading to mismatches between the original phase configuration and the new channel geometry. Thus, the reflected signals may no longer align constructively and the gain at the receiver decreases unless the IRS is reconfigured accordingly.

C. How to use `ns3IRS`

A minimal example in Listing 1 shows how `ns3IRS` can be used within a WiFi network. After creating the `IRS node` via a ns-3 `NodeContainer` (Line 1 and 2), a fixed position is assigned via a ns-3 `MobilityHelper` (see Line 4–10). Starting in Line 12, the IRS is defined with its attributes like its orientation (`Direction`), the number of elements (`N`), the spacing between the elements and the radio frequency of the signal. Note, that the spacing between the elements has to fit to the used radio frequency. Additionally, the `CalcRCoeffs` function is used optimize the IRS configuration for a specific link. It therefore requires the position of two nodes the IRS should be optimized for. The LOS distance between the two nodes as well as the length of the path via the IRS and the inbound and outbound angles of the path at the IRS will be calculated from this information. `CalcRCoeffs` calculates the phase shift at the IRS such that the reflection arrives at Rx with a given phase shift. To get optimal conditions, this phase shift (`phase_offset`) is set to 0. For example, nulling at Rx can be achieved by using π as phase shift. The two path loss models are set in Line 22–25 and applied as an `IrsPropagationLossModel` in Line 27.

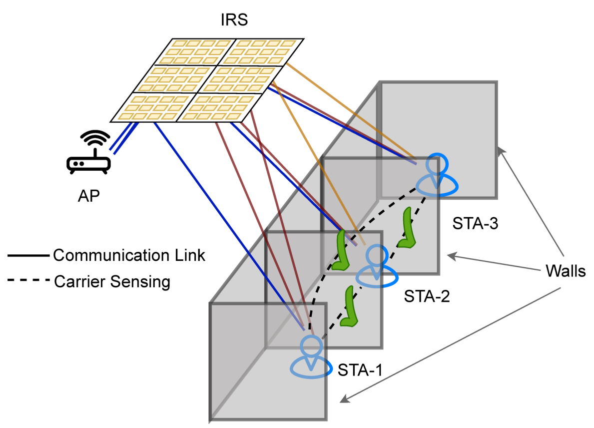
```
1  NodeContainer irs;
2  irs.Create(1);
3
4  MobilityHelper mob;
5  auto pos = CreateObject<ListPositionAllocator>();
6  pos->Add({0, 0, 0});
7  mob.SetPositionAllocator(pos);
8  mob.SetMobilityModel(
9      "ns3::ConstantPositionMobilityModel");
10 mob.Install(irs);
11
12 auto irsModel =
13     CreateObjectWithAttributes<IrsSpectrumModel>(
14     "Direction", VectorValue({0, 1, 0}),
15     "N", TupleValue<UintegerValue, UintegerValue
       ↪>({20,20}),
16     "Spacing", TupleValue<DoubleValue, DoubleValue
       ↪>({0.029, 0.029}),
17     "Frequency", DoubleValue(5.21e9));
18
19 irsModel->CalcRCoeffs(node_tx, node_rx, phase_offset);
20 irs.Get(0)->AggregateObject(irsModel);
21
22 auto irsLoss = CreateObjectWithAttributes<
       ↪LogDistancePropagationLossModel>(
23     "Exponent", DoubleValue(2));
24 auto losLoss = CreateObjectWithAttributes<
       ↪LogDistancePropagationLossModel>(
25     "Exponent", DoubleValue(5));
26
27 wifiChannel.AddPropagationLoss(
28     "ns3::IrsPropagationLossModel",
29     "IrsNodes", PointerValue(&irs),
30     "IrsLossModel", PointerValue(irsLoss),
31     "LosLossModel", PointerValue(losLoss),
32     "ErrorModel", TupleValue<DoubleValue, DoubleValue
       ↪>({0, 0.5}),
33     "Frequency", DoubleValue(5.21e9));
```

Listing 1: Usage of `ns3IRS`

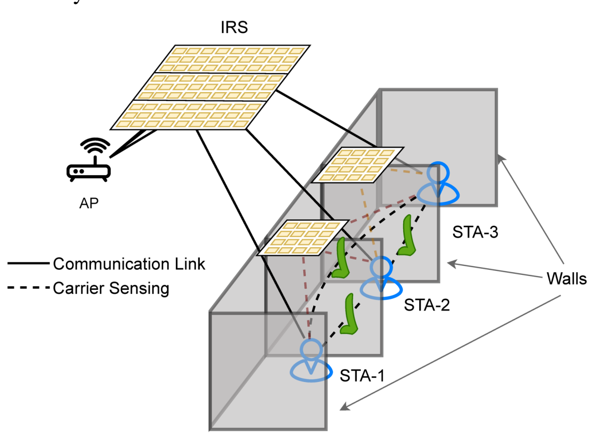
V. System Model & Problem Statement

The coverage of a Wi-Fi AP can be limited in indoor environments because of obstacles like walls. In this paper, we consider an office environment in a big hall where intermediate walls shield the different work spaces, however, they all share a common ceiling above the walls as illustrated in Figures 1 and 3. The coverage area of the Wi-Fi AP can be extended by an IRS boosting communication to the M different STAs at the work spaces. Therefore, the IRS is split into M tiles and each tile is optimized to improve the link towards one STA. This approach is denoted by *BL1: w/o RTS/CTS* throughout the rest of the paper. The IRS is placed close to the AP to increase its impact (placing it near one of the communication nodes in a single-input single-output (SISO) model gives the best results, see [24]). We consider multiple STAs (M) sending uplink traffic to the AP. However, these STAs can not hear each other, as the communication channel between them is blocked by the intermediate walls. Thus, the STAs act as hidden terminals, causing their uplink packets to collide at the AP, as CSMA/CA fails to work. Additionally, we assume a stationary setup, which can be seen as part of a nomadic scenario such that the IRS is configured once and only reconfigures in case new nodes appear.

In our model, we assume links of a log distance path loss model with path loss exponent 5.5 for the NLOS paths and 2 for the LOS paths, following the recommendations in [34]. For the central IRS, we assume 45×45 elements. It is then equally split among STAs. All nodes are using IEEE 802.11ac with a fixed data rate of 65 Mbit/s on a 20 MHz channel. The AP is positioned at coordinates $[10,\ -3.5,\ 9.5]$, and the IRS



(a) *P1: Centralized IRS*: Further splitting the IRS such that it creates connectivity between the STAs.



(b) *P2: Distributed IRS*: Adding a small, dedicated IRS near $M-1$ STA such that it creates connectivity between them.

Figure 3: Two different solutions proposed for solving the hidden terminal problem.

is placed 0.7 m away from it. The STAs are initially arranged on the xy-plane in a grid layout, with 10 m spacing between them. During the simulation, multiple runs are conducted in which the positions of the STAs are randomly altered. This change is applied in the x and y directions using values drawn from a uniform distribution in the range $[-2,\ 2]$ m.

VI. Solving the Hidden Node Problem

To solve the described hidden terminal problem, we suggest to utilize the IRS to create a common collision domain. Two approaches are proposed.

(a) We split the centralized IRS at the AP into $M(M+1)/2$ tiles, and optimize each tile such that it strengthens one link. Throughout the paper, this approach is denoted as *P1: Centralized IRS*. With this approach, instead of only creating links from the AP to the STAs, we are also creating links between the STAs by the central IRS as illustrated in Figure 3a. In the figure, for simplicity, we only show how the connectivity between the leftmost STA and the two others is created. Nevertheless, with the help of an IRS we create a virtual LOS between the STAs. All the links are bidirectional and we exploit the fact that IRSs work symmetrically.

(b) In addition to the IRS mounted close to the AP, we also install $M-1$ small IRSs close to each STA, such that they can bridge the intermediate walls between the STAs (*P2: Distributed IRS*). For each of these small IRS we choose 10×10 elements which is enough to enable carrier sensing. The IRS at the AP keeps its configuration as before, with the aim of optimizing the link between each STA and the AP, while each of the small IRSs are configured to strengthen the links towards $M/2$ STAs. The links between all M STAs are covered by making use of the symmetric links and the symmetric properties of the IRS, $M/2$ tiles are enough to boost all of the $M \cdot (M-1)/2$ links between the STAs, as we show in Figure 3b. Traditional CSMA/CA with RTS/CTS can solve the problem as well, so we are using it as a baseline, referred as (*BL2: RTS/CTS*).

VII. Results

We evaluate our proposed solutions with the help of `ns3IRS`. In the simulated office environment, there was no communication possible between the STAs and the AP without an IRS. Adding the IRS optimized for the links between AP and STAs (*BL1: w/o RTS/CTS*) now enables communication, as shown in Figure 4a. We run our simulations 30 times, for which we change the seed and position of the STAs as explained in Section V. In total, 30 s are simulated. A summary of the simulation parameters is shown in Table I.

A. Throughput

First, we analyze the average throughput of our approaches for different number of STAs and compare the results with a traditional approach where CSMA/CA with RTS/CTS is used (*BL2: RTS/CTS*). In this approach, we are using the centralized IRS optimized only for the AP to STA links. The results in Figure 4a show how the hidden nodes affect the performance

Table I: Simulation parameters

Parameter	Value
WiFi standard	802.11ac
Center frequency	5.21 GHz
Bandwidth	20 MHz
Data rate	65 Mbit/s (MCS7)
Uplink traffic (UDP, per STA)	50 Mbit/s
Simulation time	30 s
Runs	30
Number of IRS elements (centralized)	45×45
Number of IRS elements (distributed)	10×10
Number of STAs	2–10
Path loss exponent NLOS	5.5
Path loss exponent LOS	2
Distance inter-STAs	$10\,\text{m} \pm 2 \cdot [-2, 2]$ m
Mobility	static

if no countermeasures are taken. Without hidden terminals, a constant total uplink throughput of the stations is expected.

For *BL1: w/o RTS/CTS* the traditional CSMA/CA approach leads to a loss of throughput as more stations are present. This is caused by two effects. First, as more STAs are present, there is a higher probability of collisions. Especially for two STAs we see in our packet traces how the channel is divided by the stations, thereby, while one station is blocked by a high back-off, the other station can send its packets as it can benefit from the shorter back-off which comes after a successful transmission of a packet. Second, the gain for the links between STA and AP is decreased, which decreases the Signal-to-Noise Ratio (SNR) at the AP. This is important, as the ns-3 interference helper sums the energy of the overlapping parts of interfering packets and takes it as noise floor for the calculation. Stronger packets thereby can survive interference, if the interfered part of the packet is not as long and the packet is received with a sufficient power budget. Both cases are affected by the fact that the gain of the IRS is proportional to $20 \cdot \log(N)$; therefore, a half-sized or split IRS loses 6 dB of gain. Overall, we see a reduction of throughput of nearly 20 Mbit/s if 7 STAs are present compared to only 2 STAs.

BL2: RTS/CTS preformance is more linear, however, it also loses throughput if more STAs are involved due to the higher probability that the channel reservation does not work due to collision. Interestingly, for the case of two STAs, this method performs worse than *BL1: w/o RTS/CTS* due to the overhead of the additional required communication to reserve the channel.

Proposed *P1: Centralized IRS* and *P2: Distributed IRS* approaches increase the throughput by around 7 Mbit/s compared to the *BL1: w/o RTS/CTS* case for 2 STAs. However, with increasing number of users, *P1: Centralized IRS* becomes less effective as there are not enough elements available on the IRS, leading to a drop in throughput in the case of more than 5 STAs. This is caused because splitting the IRS decreases the gain for the links between the STAs and therefore makes the carrier sending less effective. For more than 5 STAs, *BL2: RTS/CTS* outperforms this approach. Due to the additional smaller IRSs, *P2: Distributed IRS* achieves around 10 Mbit/s higher throughput than *BL2: RTS/CTS* which becomes less effective (5 Mbit/s higher throughput) for 10 STAs. This

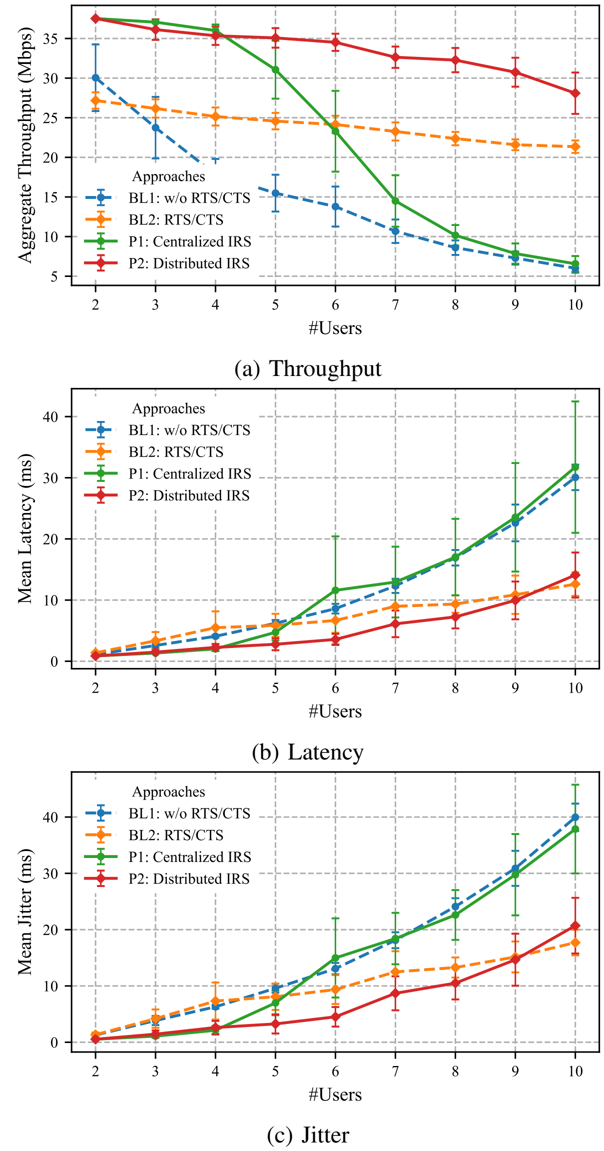


Figure 4: Influence of different approaches on throughput, latency, and jitter depending on number of users.

decrease is caused by splitting the small IRSs into more and more tiles which decreases their gain. However, *P2: Distributed IRS* outperforms all other approaches under study.

B. Latency and Jitter

The measurement of latency and jitter due to the channel access and lost packets in Figures 4b and 4c shows how both values increase as more STAs are present, which is expected. Especially, if more than 5 STAs are in use, the latency and jitter for the approach without countermeasures (*BL1: w/o RTS/CTS* and *P1: Centralized IRS*) increase rapidly. While for the first case is clear why, in the second case, similarly as before, the links supported by the IRS become weaker as fewer elements are assigned to them. This results in a 30 ms and above latency compared to latencies below 15 ms and jitter below 20 ms for the other two approaches. These values mainly result from

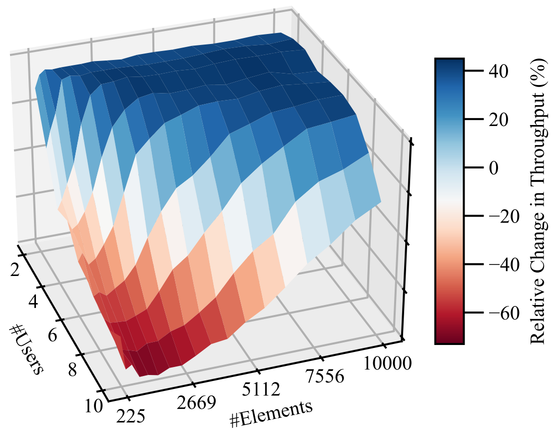


Figure 5: Relative throughput increase of *P1: Centralized IRS* in comparison to CSMA/CA with RTS/CTS baseline (*BL2: RTS/CTS*) depending on IRS size.

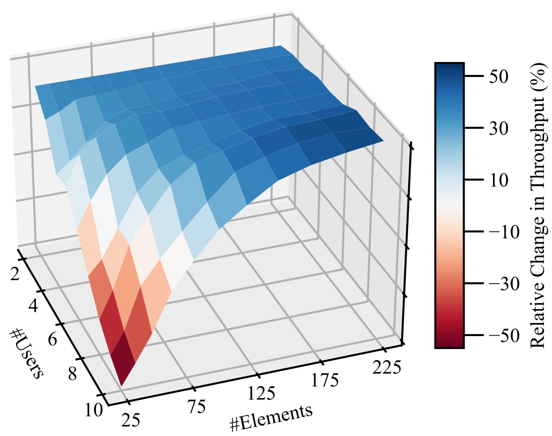


Figure 6: Relative throughput increase of *P2: Distributed IRS* in comparison to CSMA/CA with RTS/CTS baseline (*BL2: RTS/CTS*) depending on size of STAs IRS.

the high number of packet collisions if the STAs cannot sense each other. The results also reveal that the *BL2: RTS/CTS* approach has generally higher delay and jitter due to CTS waiting periods, random backoff, and a higher probability of retransmissions by contention or missed control frames.

C. Impact of IRS Size

Next, we analyze how the size of the centralized IRS affects the throughput of *P1: Centralized IRS* compared with the throughput of the baseline (*BL2: RTS/CTS*). The results in Figure 5 reveal that there is a minimal number of required elements of the IRS depending of the number of STAs as this will cause splitting the IRS into smaller tiles. For less users, the curves flatten at an increase of about 40% compared to the baseline. However, to operate in this saturation an IRS of 10,000 elements is required in case of 7 STAs. Even though we see an improvements of 6.6% for 10 STAs and an IRS of 10,000 elements, this value is way below the saturated value.

For *P2: Distributed IRS* we study the influence of the size of the small IRSs and compare the average throughput against the average throughput of *BL2: RTS/CTS*. As the results in Figure 6 show, *P2: Distributed IRS* method can achieve an increase in throughput of around 40%. Indeed, for 5 STAs this value is already achieved by 81 element IRSs, however, for 9 STAs more than 144 elements are required per IRS.

To summarize the results, it is important to note that a high gain from the IRS enables the collided packets to survive the collision, when only short parts of the packets are collided. That is how the hidden terminal problem is combated in the two STAs case, even without RTS/CTS or proposed approaches. However, when the gain from the centralized IRS diminishes, so when the number of users in the network increases, either RTS/CTS or *P2: Distributed IRS* are needed to combat the hidden terminals.

VIII. Discussions and Conclusions

In this paper, we introduced `ns3IRS` and showed that the ill-considered use of IRS can lead to the creation of hidden terminals in 802.11 WiFi networks that rely on CSMA/CA. We then proposed two strategies for solving this. The first approach (*P1: Centralized IRS*) is based on using a centralized IRS to also strengthen the inter-STA links. The second approach (*P2: Distributed IRS*) focuses on using small IRSs at the STAs' positions to enable the STAs to sense each other. These approaches can improve the average throughput by 5–10 Mbit/s compared to the baseline case. Additionally, the latency and delay are kept low, keeping the network deterministic. However, the *P1: Centralized IRS* becomes less affective or even useless if more STAs are present. It is also outperformed by *BL2: RTS/CTS* in case of the presence of more than 5 STAs for an IRS of 2025 elements. Nevertheless, the point of equality is dependent on the number of elements of the IRS. *P2: Distributed IRS* works well for a higher number of STA if the IRSs are not too small (at least 100 elements each).

The strong aspect of these solutions is that IRS needs to be configured only when a STA joins or leaves the network, and not during channel access, which is infeasible due to reconfiguration delay of IRS, under the assumption that STAs are nomadic. For 802.11 networks, this is particularly useful, given that reconfiguration is impossible with random access. It is important to highlight that both proposed solutions require installation of additional hardware components. This comes with additional costs which limits our approach. However, once IRSs are commercialized, they are expected to be relatively inexpensive. Given their passive nature, IRSs may even prove more cost-effective than massive MIMO antenna arrays and more flexible, as they are technology independent. This raises an important question about the future of communication networks: should system complexity be concentrated in the devices, as in massive MIMO systems, or distributed across the environment through technologies like IRS? Our approach advocates the latter, allowing the rest of the communication system to remain simple, straightforward and exchangeable. Nevertheless, further research is required to fully assess the implications of transferring system complexity from devices to the environment.

Future work will also focus on loosening some of the assumptions made in our system, such as the perfect channel state information knowledge required to configure the IRS and continuous phase shifts of the IRS. We like to extend our work by taking mobility, quantization errors and imperfections into account. Moreover, we plan to extend the model to support wideband IRS for wide channels like 320 MHz in Wi-Fi 7.

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