Gamifying Signals: Communications-Themed Capture the Flag for Outreach, Engagement, and Education

Federico Larroca, Gonzalo Belcredi, Romina García Camargo, Gastón García González, Lucas Inglés, Camilo Mariño, and Martín Randall

***Abstract*—This article presents and discusses a communications-themed Capture the Flag (CTF) competition designed to enhance visibility and engagement with Electrical and Communications Engineering (ECE). In response to declining enrollments in ECE disciplines worldwide, and in line with pedagogical research advocating for early technical exposure, our initiative leverages Software Defined Radio (SDR) as both a teaching tool and a medium for community building.**

The CTF features two complementary formats: a virtual edition, designed for technically advanced students and professionals, and an in-person edition, aimed at high-school students and the general public. The virtual challenges are based on recorded IQ signals, requiring participants to decode messages using SDR tools like GNU Radio, guided by appealing narrative clues. The in-person version takes the form of a treasure hunt using live radio signals—initially with SDRs and later simplified to smartphone-accessible signals such as audio, Bluetooth or Wi-Fi.

In addition to describing in detail both versions of the CTF, we share pivotal lessons learned in our five years' experience. During this time, the CTF has grown into a robust educational and outreach platform, fostering a community of SDR practitioners, supporting curriculum development, and motivating students to pursue careers in telecommunications. We are convinced that this kind of hands-on, narrative-driven technical challenges can play a significant role in demystifying complex concepts, stimulating interest in ECE, and bridging gaps between education, industry, and the public.

***Index Terms*—Software Defined Radio (SDR), Telecommunications, Capture the Flag (CTF), Tournament, Problem-based Learning**

I. Introduction

FOR over a decade, there has been a concerning decline in the enrollment of students pursuing degrees in electrical or communications engineering (ECE) [1]. This trend is not unique to these specific fields, but extends across various STEM disciplines [2]. However, ECE plays a key role in driving innovation in such strategic areas as electronics, computing and telecommunications. An illustrative example of this significance is the recent approval of the CHIPS and Science Act by the US government [3]. This legislation earmarks approximately 280 billion dollars for the advancement and production of semiconductors. Early projections suggest that this substantial investment into revamping the American chip manufacturing industry will necessitate the recruitment of roughly 50,000 professionals over the next few years [4]. This initiative, coupled with broader developments like the "5G race" and the controversial restrictions on Huawei in various Western nations [5], [6], illustrate the geopolitical relevance of ECE, especially within the telecommunications sector, and consequently the importance of reversing the dwindling enrollment of students in the discipline.

Studies into the motives behind this decline have identified several contributing factors. One historical cause is the perception among students that ECE is "difficult", leading some to either abandon their studies or switch to other majors due to low or failing grades. Other reasons include inadequate teaching quality, or the absence of technical or hands-on courses during the first years of the curriculum [1]. Conversely, studies have shown that a good communication on what ECE consists, as well as early exposure of students to its technical content, are effective tools in order to reverse this tendency [7], [8].

In this article we describe an activity in this line, and whose ultimate objective is precisely to increase the visibility of ECE, particularly telecommunications: a so-called Capture the Flag (CTF). Differently to more traditional cybersecurity CTFs, ours is communications-themed and includes two variants (virtual and in-person). Both are held during an annual general public event[1], so that even if participants may already be ECE students, prospective students or their families are also exposed to the activity and its (technical) content.

The virtual edition, designed for medium-to-advanced students (or engineers), comprises a series of challenges, each featuring a signal recording and an accompanying story. The signal is typically a modulated message using certain technology. Once found, the message is submitted to an online platform and an amount of points are earned. The group with the largest score when the tournament finishes is declared the winner (typically two weeks are provided for contestants to work on the challenges, after which winners are announced and prizes awarded).

Federico Larroca, Romina García Camargo, Gastón García González, Lucas Inglés, Camilo Mariño, and Martín Randall are with the Facultad de Ingeniería, Universidad de la República, Montevideo, Uruguay (e-mail: flarroca@fing.edu.uy; rominag@fing.edu.uy; gastong@fing.edu.uy; lucasi@fing.edu.uy; cmarino@fing.edu.uy; mrandall@fing.edu.uy). Gonzalo Belcredi is with the Institute of Communications and Navigation, German Aerospace Center (DLR), Weßling, Germany (e-mail: gonzalo.belcredizambra@dlr.de). Romina García Camargo is also with the Dept. of Electrical and Systems Eng., University of Pennsylvania, Philadelphia, PA, USA (e-mail: rominag@seas.upenn.edu). Lucas Inglés is also with IMT Atlantique, Plouzané, France (e-mail: lucas.ingles-loggia@imt-atlantique.fr).

[1]See https://idm.uy/

The signal may be as simple as an FM broadcast or as complex as digital TV or even GPS. Generating these signals involves Software Defined Radio (SDR) software [9], [10], such as GNU Radio [11], which provides several complete transceivers. Leveraging its open-source nature, we can increase the challenge by customizing the transmitter, so that the solution is not simply downloading and running a code snippet. In our experience, the accompanying story and illustration serve as key incentives for participants. Not only do they provide engaging context, making the challenge more intriguing, but they also function as valuable clues for solving the challenge (e.g. by referencing inventors or other relevant details).

We have organized five annual editions of the virtual CTF, drawing nearly two hundred participants from academia, industry, and the broader public of radio and signal processing enthusiasts. Over time, the event has established a strong sense of community: many participants return year after year, students look forward to joining as they progress through the communications curriculum, and the competition has gained visibility through its recurring presence in the University's flagship public outreach event. However, due to its technical demands, the virtual edition remains largely inaccessible to early-stage or prospective engineering students. Engaging this audience is crucial if we are to address the declining enrollment trends discussed earlier. With this goal in mind, we developed an in-person version of the CTF specifically designed to lower the barrier to entry and broaden participation.

In particular we have tried two variants of the in-person CTF, both targeted to latter years' high-school students and taking the form of a short treasure hunt. In this case, hints to the next "treasure" (flags) are provided by live signals. In the first edition, we provided a laptop and a low-cost SDR hardware for each participating team. However, the event required extensive logistics, including a short session with signed-up students to introduce the usage of SDR software and other related concepts.

For the second edition of the in-person CTF we instead transmitted signals that may be received by any smartphone (e.g. Bluetooth). This way, logistics is reduced to simply placing the transmitters, and unprepared attendants can easily participate. Furthermore, being co-located with the outreach event, the hunt follows a trail that engages participants to visit the exhibit all while interacting with different (radio) signals, further increasing the appeal of the activity. We believe that this second version of the in-person CTF has been a success, with over 150 participants of all ages in last year's edition only. We are convinced that this kind of recreational activities helps increase the visibility of ECE in general, a subject that may at first impress as too technical or even non-existent to the general public.

A. Related Work and Article Outline

Gamification has been widely adopted in engineering education as a means to enhance motivation and engagement [12], [13]. Reviews consistently report that gamified activities improve student participation and collaboration [14], [15], while also warning about possible drawbacks such as stress or increased workload when designs are not carefully balanced [16].

A particularly popular form of gamification is the CTF format, which as we mentioned before is extensively used in cybersecurity education. Numerous initiatives have demonstrated how progressively challenging, story-driven puzzles mapped to curricular outcomes can effectively develop technical and problem-solving skills [17], [18]. Frameworks have also been proposed to evaluate CTF design choices and their alignment with learning objectives [19]. While these contributions highlight the pedagogical potential of CTFs, they almost exclusively focus on security-related content and contexts.

In the area of communications engineering, SDR has emerged as a powerful educational tool. Low-cost hardware and open-source software frameworks enable students to experiment with real signals, bridging the gap between theory and practice. Reported experiences show that SDR-based labs improve understanding of modulation, synchronization, and other core communications concepts [10]

Our work brings together these two strands by translating the CTF format to the communications domain, leveraging SDR-friendly challenges that combine technical rigor with narrative-driven engagement. To the best of our knowledge, this is the first initiative that systematically applies CTF mechanics to foster both outreach and education in communications, complementing previous gamification and SDR-based efforts in engineering education.

This article is an extended version of our previous publication at TAEE 2024 [20]. Compared to the conference version, it presents updated information (including a new edition of both versions of the CTF), a more thorough discussion of several key aspects, and detailed descriptions of additional CTF challenges. Furthermore, a completely new section situates the CTF within the context of our university's communications curriculum and explains how we succeeded in cultivating a critical mass of faculty and students proficient in SDR.

The rest of the article is structured as follows. The next section presents SDR, as it is the core technology in our CTF. Section III discusses the origin of the CTF and its evolution, as well as providing context of how we incorporated SDR into research and education. In Sec. IV we discuss the virtual CTF, including the detailed description of several challenges and their solutions, as well as lessons we learned in this five editions. The in-person CTF is discussed in Sec. V, including both variants. Concluding remarks are left for Sec. VI. Further details, including additional challenges and rules, are available at the event's website https://ctf.idm.uy/.

II. Software Defined Radio

SDR is a paradigm in which software predominantly handles the signal processing tasks traditionally managed by hardware components in legacy radio communications systems. As a result, students and researchers can seize the fundamental concepts of communications and experiment with new communication systems without the need for specialized

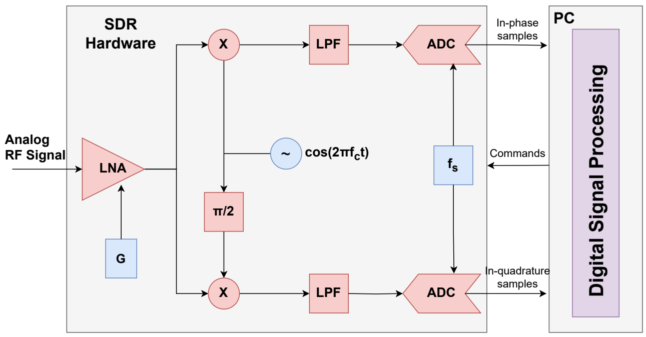

Fig. 1. Simplified diagram of a typical SDR receiver. Analog RF signals are downconverted, filtered, and digitized before being processed entirely in software on a PC. Blocks shaded in blue indicate that they are configurable by the PC.

(and expensive) equipment. This accessibility fosters a more inclusive and innovative environment where theoretical knowledge can be applied in practical scenarios, leading to a deeper understanding and faster advancements in the field.

In SDR, hardware primarily handles the task of downconverting the analog signal to baseband and transferring the samples to the PC, typically via a USB port. As illustrated in Fig. 1, the hardware section performs only the fundamental operations: multiplying the passband signal by a local oscillator, analog filtering, amplifying and sampling. This results in a complex discrete signal, commonly known as IQ data (In-phase and Quadrature components), which is then transferred to a PC where all subsequent digital signal processing is performed entirely in software.

The aforementioned operations describe the reception aspect of SDR, although naturally transmission is also possible, where a discrete complex signal is upconverted to a continuous passband signal at a certain carrier frequency. Several possible hardware models exist, differing primarily in its frequency range, sampling rate and quality of its components. Various manufacturers and vendors such as Ettus Research [21], HackRF [22] and RTL-SDR [23] offer a range of equipment options to suit different requirements.

In terms of software, there are several programs with specific functionalities, such as simply acting as a spectrum analyzer [24], or implementing more advanced technologies such as computing the position through the signals provided by a Global Navigation Satellite System (e.g. GPS or Galileo) [25], decoding the signal of certain imagery satellites [26] or even setting up a complete cellular network [27]. The vast majority of these are open-source, enabling innovation and experimentation, which we leveraged in our CTF.

Most of this software is programmed from scratch, basically starting from the hardware drivers. When experimenting, prototyping or teaching, it is natural to first rely on a framework that simplifies some of the processing involved. This is exactly the role of GNU Radio [11], an open-source framework where the complete processing chain is represented by a series of interconnected blocks, forming a so-called *flowgraph* (see Fig. 2). Each of these blocks performs a well-defined functionality on the data flow (e.g. filtering, forward error correction,

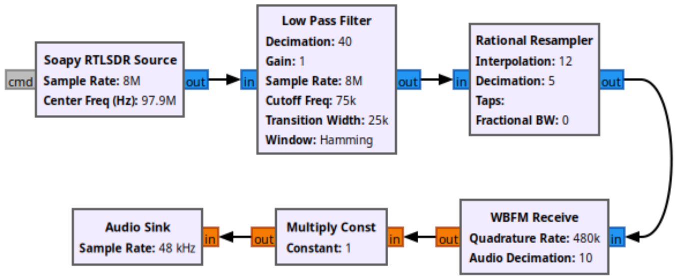

Fig. 2. GNU Radio flowgraph implementing a basic FM receiver. It includes signal acquisition, filtering, resampling, demodulation, and audio output blocks.

etc.), and several of them are already included in the base installation. In any case, it is relatively straightforward to create new blocks (which may be programmed either in C++ or Python), and there is a vast list of contributed additional blocks and modules [28], some of which implement complete systems such as Digital TV [29] or LoRa [30].

As an example, Fig. 2 shows a GNU Radio flowgraph implementing an FM radio receiver. The source block corresponds to an RTL-SDR device, which interfaces with the hardware and allows adjusting parameters such as sample rate, center frequency and gain (corresponding to f_s, f_c and G in Fig. 1). The device outputs raw complex baseband samples, which are typically contaminated with noise. A low-pass filter is applied to minimize this noise and isolate the desired signal. Next, a resampling block adjusts the sampling rate to match the requirements of the demodulator. The WBFM Receive block then demodulates the FM signal and outputs the recovered audio, which can be listened to or further processed. This type of visual programming environment is especially useful for introducing signal processing concepts in a hands-on and intuitive way.

In virtual CTFs, the signals provided to participants are typically generated using SDR frameworks such as GNU Radio, or custom scripts written in Python or other tools. These signals are delivered as stereo WAV files, where each channel (left and right) corresponds to the real and imaginary parts of the IQ samples, respectively. Each WAV file effectively replaces the RTLSDR Source block and serves as the input to a similar demodulation chain as the one illustrated in Fig. 2. Although we use a sampling rate significantly higher than that of standard audio (to accommodate the signal's bandwidth), this format is compatible with a wide range of software tools, GNU Radio among them.

III. Origin and Context

Before delving into further details of the CTF, it is important to first understand the motivations behind its creation and the academic context within our University's communications curriculum. The inaugural edition of the tournament took place in 2020, amid the height of the COVID-19 pandemic and the widespread enforcement of stay-at-home measures. That year, the School of Engineering's flagship outreach event (Ingeniería deMuestra - IdM), which typically attracts thousands of visitors to explore student projects and research initiatives, was transitioned to a fully virtual format. The organizing committee requested that participants contribute short videos or webpages to be showcased during the two-day event. However, we felt that such static content would struggle to capture attention or offer meaningful engagement.

Instead, we proposed an interactive and technically rich alternative: a communications-themed CTF tournament. Drawing inspiration from similar initiatives in the GNU Radio and Ekoparty communities, we designed a series of challenges that could immerse participants in the world of radio signals and signal processing.[2]

Naturally, to decode the provided signals, teams are expected to possess a certain level of proficiency in SDR. The required skills vary depending on the complexity of each challenge, ranging from relatively simple tasks such as demodulating AM radio or extracting RDS data from FM broadcasts, to more advanced objectives like configuring and using software capable of demodulating digital television signals. Each challenge is accompanied by a narrative that not only provides engaging context but also offers subtle hints about the underlying technology used in the recording, helping participants determine an appropriate decoding strategy.

Thus, a critical factor in the sustained success of the virtual CTF has been achieving a critical mass of students and faculty proficient in SDR technologies. In what follows, we describe how this technical foundation was built over the past decade and how SDR has been systematically integrated into our institution's communications curriculum.

Our research group's engagement with SDR dates back to 2012, with the acquisition of our first hardware (two USRP N200 devices from Ettus Research). Recognizing the steep learning curve associated with proficient SDR usage, we adopted what we believe to be the most effective strategy for learning: teaching the subject in a course. This began in 2013 with the launch of a hands-on graduate course in wireless communications, structured around laboratory exercises using GNU Radio. These labs emphasized the functioning of real receivers, covering critical topics such as time, phase, and frequency synchronization, as well as equalization, subjects not typically included in communication courses.

However, a deep understanding of GNU Radio and its inner working was not actually achieved until we undertook the implementation of a real-world full system. A milestone for our group was the publication of `gr-isdbt` in 2015, the first open-source ISDB-T receiver, which was later extended into a full transceiver in subsequent work [29], [31]. These and other projects were developed in collaboration with both undergraduate and graduate students as part of their thesis work.

At this point we were confident that SDR was an extraordinary tool for teaching communications, applicable far beyond the limited scope of a graduate course [9]. This led to the 2016 introduction of a third-year undergraduate course (our Engineering degree is five years long) focused on signal processing and analog modulation, taught entirely using GNU Radio and affordable RTL-SDR dongles. This cohort of students represents what we consider the first "SDR-native" generation trained within our school.

Two years later we took a further step into increasing the visibility of SDR, and leveraging its appeal as a motivation for students we offered the first edition of a first-year hands-on course [32]. Despite their initial background, as students at this point have minimal prior knowledge of programming or signal processing, by the end of the semester they were able to build and operate functional receivers for applications such as satellite imagery or ADS-B tracking. In parallel, other intermediate to advanced communications courses (traditionally centered on MATLAB) have been restructured around GNU Radio, allowing for real-time demonstrations and interactive assignments that better illustrate theoretical content.

This systematic integration of SDR throughout the curriculum means that, by the time students begin their final thesis projects, they possess a solid foundation in practical signal processing and system design. As a result, they are well-prepared to tackle complex and ambitious challenges, such as the recent implementation of a TEMPEST side-channel attack receiver [33], [34] or a low-cost AIS transmitter [35], among many other examples.

This process has generated an SDR community that includes both students and alumni, and the virtual CTF may be considered as another activity to foster and amplify this community. During the CTF, participants are not only able to apply their SDR knowledge to challenging scenarios, but it also promotes collaboration and strategy sharing among team members. This environment leads to deeper learning and improved problem-solving capabilities, establishing a strong foundation for professional growth in SDR.

IV. Virtual CTF

A. Challenges and flags

As we mentioned before, the virtual CTF consists of recorded signals wherein lies a so-called *flag* (i.e. the message), which can be hidden through a complex or uncommon modulation (among other variants), with a wide range of complexity degrees. The flag may be for example some random characters, or the answer to a question posed in the challenge's narrative, and may take the form of an audio (where the flag is plainly spoken or encoded for instance using Morse), a text (typically encoded in ASCII to avoid over-complicating the challenge), an image or even a video. In any case, the flag has to be clearly discernible in order to avoid confusion and frustration in the participants. To this end, except for very rare exceptions, they should always start with the word "flag". Furthermore, if the flag is in the form of audio (such as if the challenge is to demodulate an AM radio), the flag should be spelled in the NATO phonetic alphabet (e.g. "alpha" for the letter 'a' or "bravo" for 'b').

As the aim of the competition is to engage students, we try to make it so that even freshmen students can always solve at least some of the proposed challenges. In order to motivate these students' participation, we have implemented

[2] A particularly influential reference was Mariano Marino's "Radio Experimentación" space, formerly hosted as part of Ekoparty. Although the original webpage is no longer available, Ekoparty continues to be an active event in the global security and hacking community (see: https://ekoparty.org).

a two-tier system: students until third year compete at the so-called "Marconi" category, whereas the "Shannon" category is reserved for more advanced students and professionals. The categories' names were chosen as a symbolic parallelism: "Marconi" refers to the pioneering era of wireless communication technologies, thus representing the introductory or beginner level, while "Shannon" evokes the foundations of modern digital communication theory, and is therefore associated with the more advanced or senior level. Challenges are the same, but prizes are awarded separately for each category. Teams have to download the recording and find the hidden flag, which is usually done through the usage of software such as Python or GNU Radio, following the SDR paradigm and making it appealing to our SDR community. The challenges' complexity is associated to points, and teams have approximately two weeks to sum as many points as possible. More explicit clues than the accompanying stories are also available, but they cost points. The whole competition is hosted using the open-source CTFd platform [36] in one of our local servers. A Discord channel is used to communicate with participants, typically to answer to doubts or announce new challenges.

A fundamental aspect of the virtual CTF has been the narrative behind the challenges: creative stories transporting the reader around the world and through the telecommunication's development and history, varying on their tone from humor to terror, from fictional history to science fiction, and so on. Although we describe a few of them in what follows, the curious reader can find last year's virtual challenges still available at https://ctf.idm.uy/grabado/, and also check the exciting scoreboard's movements.

We have also established collaborations with other research groups or initiatives for further engagement. For instance, during 2021 and due to the pandemic, a group of students built a copy of the Engineering school's building in Minecraft so that new students, that had not had the opportunity to know the building due to the stay-at-home orders, could walk through the campus at least virtually [37]. We asked these students to include a couple of Non-Playable Characters (NPCs) that provided clues about some of the challenges. More recently, the cybersecurity group at our school contributed a challenge regarding a rogue AI that took over an enterprise system, including an actual website to interact with the chatbot. This kind of context and extras are a vital ingredient to the overall experience.

We now introduce six challenges that we find representative of the complexity levels. We start with a simple digital challenge that is composed of three intertwined parts: unlocking the first flag opens up the second challenge, and so on. We then depict three more complex challenges, requiring customizing receivers suggested by the accompanying story. Finally, in 2023, we decided to include challenges involving the use of machine learning algorithms, as the theme of the event that framed the CTF was artificial intelligence. We found that this is an interesting path for garnering even more participants into the competition, and we present two such challenges. In total, each CTF consists of about 20 challenges, requiring the contributions of at least 5 people so that challenges remain varied and non-repetitive.

B. Challenges

1) The Origin: This is a simple challenge aiming to motivate participants: the flag is modulated through a combination of PSK and ASK, with a recorded sound on top of it and added noise to make it a bit more confusing. As the years' theme was machine learning, the story takes us back to 1997 at the time when Yann LeCun is working on the LeNet project [38]. The second and third challenges continue on the digital modulation style, adding a bit of complexity but still aiming for the whole range of teams' expertise. The three-stages, absolutely fictional, and humorous story, narrates how this research was actually stolen from a PhD candidate of our University during a short visit from professor LeCun. In this case, the accompanying narrative serves purely as entertainment. The last phase of the challenge switches to computer networks by using telnet and SSH (network protocols that allow remote access to a device's command-line interface), where we provide a file including the packet exchanges in the popular pcap format instead of a WAV.

2) Search and Rescue & Buried in Noise: In this case, and differently to the previous challenge, the accompanying story is key in finding the flag. The tale goes about a submarine that is lost in the ocean and the participants must help the rescuers find the location of the vehicle on a given map grid. The damaged submarine manages to transmit bursty messages with an unknown preamble, and the story suggests that transmissions are synchronized with UTC since the submarine has a GPS with a PPS output. Teams are provided with an IQ file synchronized with UTC that has the sum of the received signals by three different vessels with known locations.

We are thus dealing with a basic ranging problem, although we have two extra complications: an unknown preamble and we only have the sum of the received signal by each vessel. The former is solved through simple visual inspection, which reveals that one of the transmissions is received without interference from the other two, so the preamble is easily obtained. The latter complication is somewhat challenging, as we do not know to which vessel each reception corresponds. Although several solutions exists, the simplest one is to assume that the submarine emitted at the rising edge of the PPS (i.e. $t = 0$ in the recording) as suggested by the story and calculate the elapsed time between the transmission and the reception in each of the vessels. In order to get a good approximation of the submarine's location, and specially considering that the signals are contaminated with AWGN noise, a good way to solve the problem is calculating the correlation of the signal with the previously obtained preamble in order to obtain the starting time of the reception at each vessel. With the elapsed time and the speed of light value they can convert this time into a distance. Participants can then plot the three circles on a map grid, and spot in which grid element they intersect to obtain the flag as shown in Fig. 3. Other possible solutions exist, such as computing the auto-correlation of the signal and drawing ellipses depending on the time between peaks.

As a sequel of the previous, in the challenge we called *Buried in Noise* the type of transmission changes, and the submarine that is now escaping from another ship utilizes a

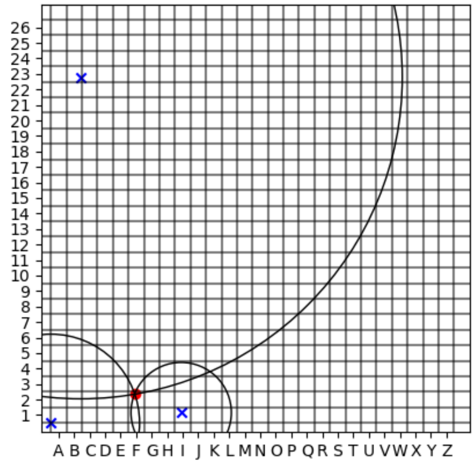

Fig. 3. Map with the solution of the *Search & Rescue* challenge: the flag is the grid element of the intersecting circles representing the location of the lost submarine.

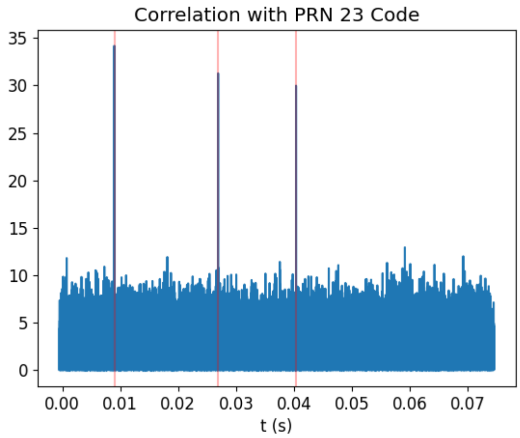

Fig. 4. The cross-correlation between the recorded signal and the PRN 23 Code can be used to solve the ranging problem in the challenge *Buried in Noise*.

Code Division Multiple Access (CDMA) scheme with the GPS Code PRN 23. Just as in the previous part, we are dealing with a ranging problem but as the signals are buried in noise the participants must first synthesize the GPS signal code and then obtain the correlation peaks to calculate the starting time of the reception (see Fig. 4). Perhaps without realizing it, participants end up recreating the fundamental principles underlying GNSS navigation.

3) Pale Blue Dot: The text of this challenge starts with an extract of Carls Sagan's book *Pale Blue Dot: A Vision of the Human Future in Space* [39] reflecting about the famous photography taken by the Voyager 1 in 1990, with the Earth seen as a "mote of dust". The text is placed together with the mentioned photo and a recorded signal with no further instructions. Only with this information the participants are supposed to make a connection with the Voyager 1 mission and its golden record containing sounds and images from the earth. They will very quickly find the image in Fig. 5 which has instructions on how to decode the messages. The signal provided is a modified version of the original containing an extra image from the Earth referencing the flag.

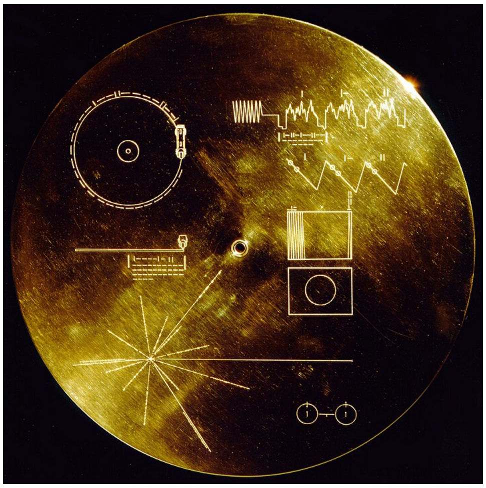

Fig. 5. The Voyager golden record containing sounds and images from the Earth [40].

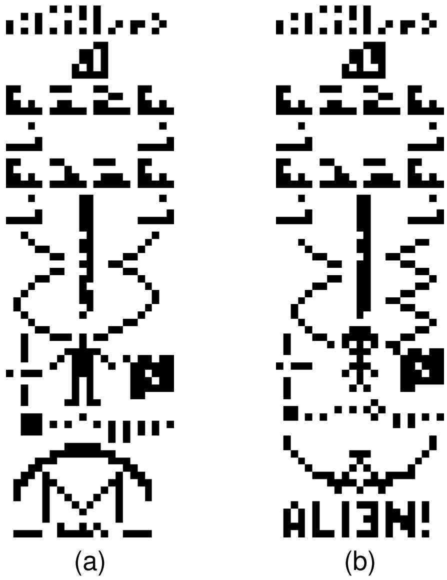

Fig. 6. (a) The original Arecibo message consists of 1679 bits of information that can be arranged in its prime factor decomposition 73×23, with 73 rows and 23 columns. (b) The solution of the challenge displays an alien figure and the corresponding flag.

4) Arecibo: This challenge served as a tribute to Arecibo's radio telescope, which collapsed in 2020. Participants must help Dr. Eleanor Arraway identify a mysterious signal with a center frequency of 2380 MHz. The text guides the reader to investigate the Arecibo message transmitted in November 1974 and directed to the globular cluster M13 [41]. The message designed by Frank Drake and Carl Sagan conveys information about our solar system, our planet, and the human species. The message was modulated with FSK with 10 Hz of bandwidth and a transmitting power of 2×10^{13} W. Now, 46 years later, participants must decode the signal; will they find proof of extraterrestrial intelligence or just discover another hoax like the one of Chilbolton's crop? The original Arecibo message and the decoded image from the challenge are shown in Fig. 6.

5) The Oldest Writings: The narrative of this challenge was rooted in a real event, concerning the discovery of what are believed to be the oldest writings uncovered to date, dating back 5,500 years. These inscriptions belonged to the Harappan or Indus civilization and are thought to be undecipherable as they belong to a dead language and, unlike ancient Egyptian, no Rosetta Stone exists to aid in translation. One hypothesis regarding the content of these writings is that they describe the contents of vessels found alongside them.

The fictional part of the story involves archaeologists enlisting the player's help, at least to determine the number of objects referenced in each inscription, to corroborate whether they correspond to the number of objects in the vessels.

For this task, the player was provided with three files, each purportedly containing a vectorization of a writing. The challenge, though not explicitly stated, lays in discerning how many clusters the samples in each file could be separated into. To avoid ambiguities in results due to the technique used, the data were generated with high-dimensional Gaussian distributions, ensuring they did not overlap. Consequently, methods such as K-Means made it straightforward to determine the number of clusters.

6) Operation Keystroke: In this challenge, the player takes on the role of an analyst assisting a Soviet spy in decoding secret messages. The spy has successfully planted a hidden microphone in an enemy facility where classified information is being typed on a typewriter. However, the recordings only capture the sound of keystrokes, without any actual spoken content.

The challenge consists of two phases. In the first and simpler phase, the player must listen to a recording featuring the repeated sound of a single key and determine which letter or number it corresponds to. The second, more complex phase, presents a sequence of keystrokes forming the name of a city that is strategically crucial to the spy's mission, which the player needs to correctly identify.

To aid in this task, the player is provided with a set of reference audio clips, each associated with a specific key (all letters of the alphabet and numbers 0 through 9), serving as a guide to compare and decipher the sounds captured in the secret recordings.

C. Evaluation and Discussion

The number of participants has increased steadily over the years, as shown in the blue bars of Fig. 7. In 2024 we welcomed more than three times the participants of our inaugural CTF in 2020. To keep improving the activity, we hold an "after-CTF" session about a week after the event. This informal gathering allows us to review the challenges with attendees, fosters a stronger sense of community, and motivates participants to return the following year. Our evaluation draws on conversations at these gatherings and on a brief anonymous survey conducted after the 2023 edition.

Most participants are senior undergraduates in electrical or telecommunications engineering (around 25 years old), though we also attract students from computer science, mechanical engineering, and a noteworthy share of industry professionals

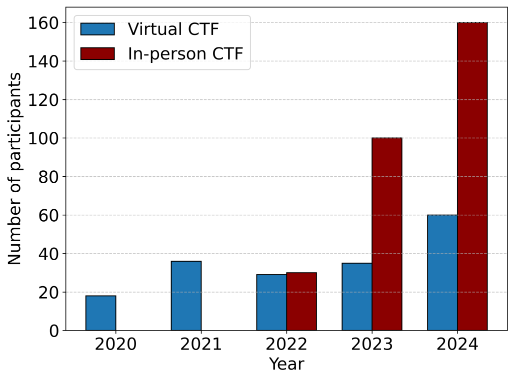

Fig. 7. Evolution of participants in the Capture the Flag over the years.

(about 30% according to the survey). After taking part once, the majority sign up again the following year. In fact, the survey indicates that 100% of respondents would participate again and would recommend the activity to their peers, reinforcing the event's appeal and sustainability. Regarding effort, more than half of the respondents reported investing at least four hours in the challenges (where more than one third dedicated over eight hours), underscoring their commitment and engagement.

Participants, including industry professionals, consistently say the CTF teaches them something new (over 80% according to the survey). Challenges drawn from adjacent areas, such as machine learning, are especially popular. Narrative back-stories, whether humorous or historical, further boost motivation, but only when they embed concrete hints for solving the tasks; otherwise they risk becoming frustrating. Finally, having a handful of introductory puzzles, like *The Origin* mentioned earlier, is repeatedly cited as a welcoming ramp that encourages newcomers to dive in. In fact, the survey indicates that 60% of the participants perceived the challenges as "difficult" but not overwhelmingly so, with only a small minority describing them as "very difficult". Furthermore, approximately three quarters felt they already had the necessary knowledge to participate, although several comments indicated that the competition also served as an opportunity to push beyond their comfort zone.

On the other hand, over the years we have learned several hard truths. Firstly, and arguably most importantly, participants will exploit any loophole. If submission attempts are unlimited and the answer space is small, some teams inevitably resort to brute-forcing, which can overload our modest platform. For instance, in the *Operation Keystroke* challenge, a group found the name of the city by submitting all cities with the number of letters that they heard in the provided recording. The limit on attempts therefore has to strike a careful balance: tight enough to discourage guessing yet generous enough not to hinder legitimate exploration or errors.

A second, recurring issue is that some teams deliberately "bank" correct flags, holding them back so rivals believe they are lower in the scoreboard, then submitting many solutions just before the deadline. We are evaluating two countermeasures. The first is to introduce time-limited challenges that appear and vanish on fixed days, obliging teams to upload their solutions while the window is open. The second is a dynamic scoring scheme in which every challenge starts with the same value and that value is divided among the teams that solve it as the game progresses. Because points would no longer signal difficulty under this system, we would supplement them with a star rating to indicate the complexity of each task.

V. In-person CTF

As previously mentioned—and as evident from the earlier challenges—the virtual CTF assumes a certain technical background, including at least basic familiarity with topics like frequency analysis or signal processing. As such, it is not well suited to audiences like high school students. The challenges were originally designed for university students, professionals, and technically inclined amateurs. However, after a couple of successful virtual editions, it became clear that we needed to broaden our target audience.

With the pandemic restrictions finally lifted, we decided to implement an in-person CTF specifically targeted to the non-initiated audience of the event that frames the CTF. We tried two variants of this version. The first one required the use of an SDR receiver (which we provided) and was thus still somewhat complex. The following year we tried an even simpler CTF, which only requires a smartphone and we believe serves our objectives best. In any case, we discuss both versions in the sequel, since both are valuable and there are lessons to be learned from them. In fact, the more technical version has been re-used and adapted for other general public activities in our University [42].

A. Technical in-person CTF

The competition consisted of a treasure hunt across the campus' buildings. Participants were divided into teams of 2-4 people, which were registered before the event. The platform to track the progress of each team was very similar to the one used in the virtual CTF, except that a single challenge is available at first, and solving it (by entering the correct flag) unveils the next challenge. This process is repeated until completion of the treasure hunt.

In this case, each challenge's narrative provides hints to the position of the next "treasure" (e.g. the campus' library) and a certain number of stations need to be visited. In each of these places a signal of some sort is to be received, for which an SDR and a laptop is provided to the group. Decoding the message in the signal provides the flag, and upon submitting it to the website the next challenge is available. The team that completes all the challenges in the shortest time wins.

The in-person CTF was first introduced in 2022 and featured four stations distributed across the university campus. At each station, a modulated signal carrying an encoded message was transmitted using GNU Radio. These messages included: audio recordings modulated using AM; images of the RF spectrum generated with the *gr-paint* module [43]; Morse code transmitted via continuous wave; and a signal modulated with FM.

The primary challenge lay in correctly receiving the signals and determining the location of the next station—especially since many participants had never used a software-defined radio (SDR) before and were not university students. To support learning and exploration, participants were not only allowed but encouraged to research relevant topics online during the competition.

Twelve teams participated in this first edition, totaling approximately 30 participants. While the event achieved its goals of engaging more people and providing fun, hands-on challenges, several areas for improvement were identified. The game's design was not yet intuitive enough, and it lasted longer than the intended 20–30 minutes. The stations were spread far across the campus, making it difficult to locate lost participants and monitor whether transmitters were functioning properly.

Perhaps most importantly, it proved challenging for high school or first-year university students to operate an SDR and its corresponding software effectively. A one-hour crash course was offered before the event to enrolled participants, but this introduced complications. Since the course was required to participate, anyone who showed interest during the event could not join. Logistics were also complex, as we had to lend a laptop and SDR to each team and assign them specific time slots.

B. Smartphone-based in-person CTF

The second version of the in-person CTF took place for the first time in 2023, with the primary goal of addressing the challenges encountered in the previous experiences. In particular, we aimed to ensure that anyone visiting the event could participate without prior preparation. To achieve this, we redesigned the treasure hunt to require only a smartphone, making the activity more accessible and inclusive for all attendees.

Since the only required equipment was a phone with Internet access, prior registration was no longer necessary. This change significantly lowered the barrier to entry and led to a substantial increase in participation. Even children showed interest and successfully completed the competition, accompanied by an adult. As shown in Fig. 7 (red bars), participation rose sharply following the removal of the registration requirement.

The challenges were also further simplified. This time, each included a brief description that offered clues not only about the location of the next station—now a specific area within the event—but also about which smartphone interface to use to retrieve the flag. For example, one station featured a phone broadcasting a Bluetooth signal. As the flag was embedded in the device name, it sufficed to check the list of available Bluetooth devices in the Settings app of any nearby smartphone to solve the challenge. Similarly, another challenge used a Wi-Fi access point whose SSID contained the flag. A third challenge employed a speaker emitting a sound whose frequency spectrum revealed the flag. For this harder task, we explained that specific apps could be downloaded to a smartphone to allow analysis of the frequency spectrum. As this challenge was the first in the treasure hunt, we were present to help participants understand the app and decode the message. In the 2024 edition, we expanded on these ideas, including a flag hidden at another exhibition stand. Additional possibilities—such as using GPS, NFC, or other smartphone interfaces—are being considered for future editions to further diversify the challenge formats.

We are confident that this second edition achieved several key objectives. It enhanced the visibility of the ECE discipline among prospective students and the general public, while also serving as an engaging introduction to our University for high school participants. Furthermore, it showcased potential areas of study and demonstrated that hands-on challenges like these can be valuable and accessible learning experiences. Notably, the smartphone-based CTF has consistently been won by high school students, confirming that we are successfully reaching our intended audience.

VI. Conclusions

We have presented a communications-themed Capture the Flag (CTF) tournament, with the objective of increasing the visibility among the general public and fostering a community in the discipline of Electrical and Communications Engineering (ECE). Two different but complementary versions address each of these challenges. Firstly, an in-person CTF, where anyone with a smartphone can participate, and a virtual CTF, where technically advanced participants are expected.

In the in-person case, we have found that a key to its success lies precisely in its simplicity. Given its treasure hunt format, placing the stations so that it results in an interesting walk around the event that hosted the CTF proved a real attraction for participants. This not only captures the interest of attendees but also allows prospective students and the general public to grasp the significance of ECE in everyday devices like smartphones. While this importance may seem obvious to technical individuals, it is often (and quite surprisingly) not commonly recognized.

In the virtual case, we have successfully managed to create a community around the event, with numerous participants returning to register year after year. We attribute this engagement to thoughtfully designed challenges that span several levels of difficulty, but complemented by engaging narratives that diverge from the typical "exam" format sometimes found in problem-solving instances. Looking ahead, we aspire to broaden this community further by potentially transforming the competition into an international platform. While we have welcomed participants from abroad in the past, in order to foster further growth we are considering measures such as making the challenges accessible to english-speaking participants (at least the accompanying story; spoken flags can be understood since we use the NATO phonetic alphabet), enhancing our outreach and strengthening coordination by garnering endorsements from other universities or involving them in the organization. While these initiatives are still prospective, we believe they offer a feasible path toward broader adoption and a stronger, globally connected SDR and communications education community.

Finally, an important aspect will be not only to sustain participation but also to better understand its impact through systematic evaluation. Both instances of the CTF have been met with strong enthusiasm from participants. A valuable next step will be to implement a more structured feedback process, enabling us to collect systematic input and thus guide yearly improvements. To this end, in the upcoming edition we plan to include a challenge that reveals its flag only upon completing a short survey, thereby gathering participant feedback in a natural and engaging manner.

References

[1] T. Long, "Short circuited: Electrical engineering degrees in the united states," *Information Technology & Innovation Foundation*, 2023. [Online]. Available: https://itif.org/publications/2023/04/24/short-circuited-electrical-engineering-degrees-in-the-united-states/

[2] A. Sithole, E. T. Chiyaka, P. McCarthy, D. M. Mupinga, B. K. Bucklein, and J. Kibirige, "Student attraction, persistence and retention in stem programs: Successes and continuing challenges." *Higher Education Studies*, vol. 7, no. 1, pp. 46–59, 2017.

[3] "Chips and science act," https://www.congress.gov/bill/117th-congress/house-bill/4346, August 2022, public Law No. 117-167.

[4] P. Patel, "Building a U.S. semiconductor workforce: CHIPS act-funded new fabs are spawning university programs," *IEEE Spectrum*, vol. 60, no. 6, pp. 28–35, 2023.

[5] S. Jones, "Germany orders ban on chinese companies from its 5g network," *Financial Times*, July 2024. [Online]. Available: https://www.ft.com/content/aacd77a2-048a-489e-98f8-b9f436e448b6

[6] L. Chadwick, "Banning chinese companies huawei and zte from 5g networks 'justified', eu says," *Euronews*, June 2023. [Online]. Available: https://www.euronews.com/next/2023/06/15/banning-chinese-companies-huawei-and-zte-from-5g-networks-justified-eu-says

[7] A. Sahin, H. C. Waxman, E. Demirci, and V. S. Rangel, "An investigation of harmony public school students' college enrollment and stem major selection rates and perceptions of factors in stem major selection," *International Journal of Science and Mathematics Education*, vol. 18, no. 7, pp. 1249–1269, 2020.

[8] E. N. Corin, G. Sonnert, and P. M. Sadler, "The role of dual enrollment stem coursework in increasing stem career interest among american high school students," *Teachers College Record*, vol. 122, no. 2, pp. 1–26, 2020.

[9] V. González-Barbone, P. Belzarena, and F. Larroca, "Software defined radio: From theory to real world communications," in *2018 XIII Technologies Applied to Electronics Teaching Conference (TAEE)*, 2018, pp. 1–7.

[10] A. M. Wyglinski, D. P. Orofino, M. N. Ettus, and T. W. Rondeau, "Revolutionizing software defined radio: case studies in hardware, software, and education," *IEEE Communications magazine*, vol. 54, no. 1, pp. 68–75, 2016.

[11] "GNU Radio. The free & open software radio ecosystem ," https://www.gnuradio.org/.

[12] G. Barata, S. Gama, J. Jorge, and D. Goncalves, "Engaging engineering students with gamification," in *2013 5th International Conference on Games and Virtual Worlds for Serious Applications (VS-GAMES)*, 2013, pp. 1–8.

[13] M.-B. Ibáñez, Di-Serio, and C. Delgado-Kloos, "Gamification for engaging computer science students in learning activities: A case study," *IEEE Transactions on Learning Technologies*, vol. 7, no. 3, pp. 291–301, 2014.

[14] C. F. Barreto and C. França, "Gamification in software engineering: A literature review," in *2021 IEEE/ACM 13th International Workshop on Cooperative and Human Aspects of Software Engineering (CHASE)*, 2021, pp. 105–108.

[15] G. P. Gasca-Hurtado, M. C. Gómez-Álvarez, J. A. Hincapié, and V. V. Zepeda, "Gamification of an educational environment in software engineering: Case study for digital accessibility of people with disabilities," *IEEE Revista Iberoamericana de Tecnologias del Aprendizaje*, vol. 16, no. 4, pp. 382–392, 2021.

[16] S. Tonhão, M. Shigenaga, J. Herculani, A. Medeiros, A. Amaral, W. Silva, T. Colanzi, and I. Steinmacher, "Gamification in software engineering education: a tertiary study," in *Proceedings of the XXXVII Brazilian Symposium on Software Engineering*, ser. SBES '23. Association for Computing Machinery, 2023, p. 358–367.

[17] V. Švábenský, P. Čeleda, J. Vykopal, and S. Brišáková, "Cybersecurity knowledge and skills taught in capture the flag challenges," *Computers Security*, vol. 102, p. 102154, 2021.

[18] K. Leune and S. J. Petrilli, "Using capture-the-flag to enhance the effectiveness of cybersecurity education," in *Proceedings of the 18th Annual Conference on Information Technology Education*, ser. SIGITE '17. Association for Computing Machinery, 2017, p. 47–52.

[19] R. Raman, S. Sunny, V. Pavithran, and K. Achuthan, "Framework for evaluating capture the flag (ctf) security competitions," in *International Conference for Convergence for Technology-2014*, 2014, pp. 1–5.

[20] F. Larroca, G. Belcredi, R. García, G. G. González, L. Inglés, C. Mariño, and M. Randall, "Building a radio community across students, industry and enthusiasts with capture the flag," in *2024 XVI Congreso de Tecnología, Aprendizaje y Enseñanza de la Electrónica (TAEE)*, 2024, pp. 1–6.

[21] "Ettus Research, An NI Brand," https://www.ettus.com/.

[22] "Great Scott Gadgets," https://greatscottgadgets.com/hackrf/.

[23] "Rtl-sdr.com. rtl-sdr (rtl2832u) and software defined radio news and projects. also featuring airspy, hackrf, fcd, sdrplay and more." https://www.rtl-sdr.com/.

[24] "Gqrx SDR," https://www.gqrx.dk/.

[25] "GNSS-SDR. An open-source Global Navigation Satellite Systems software-defined receiver." https://gnss-sdr.org/.

[26] "SatDump. A generic satellite data processing software," https://www.satdump.org/.

[27] "OpenAirInterface," https://openairinterface.org/.

[28] "CGRAN: The Comprehensive GNU Radio Archive Network," https://www.cgran.org/.

[29] F. Larroca, P. Flores-Guridi, G. Gómez, V. González Barbone, and P. Belzarena, "An open and free isdb-t full seg receiver implemented in gnu radio," in *Wireless Innovation Forum Conference on Wireless Communications Technologies and Software Defined Radio (WInnComm 16), Reston, Virginia, USA, 15-17 mar., 2016.*, 2016.

[30] J. Tapparel, O. Afisiadis, P. Mayoraz, A. Balatsoukas-Stimming, and A. Burg, "An open-source lora physical layer prototype on gnu radio," in *2020 IEEE 21st International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, 2020, pp. 1–5.

[31] F. Larroca, P. Flores-Guridi, D. Artenstein, L. Inglés, and G. Morales, "Ultra-cheap sdr digital television transmission: Isdb-t with an osmo-fl2k and an rtl-sdr," *Proceedings of the GNU Radio Conference*, vol. 5, no. 1, 2020.

[32] G. Belcredi, M. Randall, C. Rattaro, and P. Belzarena, "Satellite and aircraft communications through sdr as an introduction to telecommunications and electrical engineering," in *2020 XIV Technologies Applied to Electronics Teaching Conference (TAEE)*, 2020, pp. 1–7.

[33] S. Fernández, E. Martínez, J. Varela, P. Musé, and F. Larroca, "Deep-tempest: Using deep learning to eavesdrop on hdmi from its unintended electromagnetic emanations," in *Proceedings of the 13th Latin-American Symposium on Dependable and Secure Computing*, ser. LADC '24. Association for Computing Machinery, 2024, p. 91–100.

[34] F. Larroca, P. Bertrand, F. Carrau, and V. Severi, "gr-tempest: an open-source gnu radio implementation of tempest," in *2022 Asian Hardware Oriented Security and Trust Symposium (AsianHOST)*, 2022, pp. 1–6.

[35] R. García, M. Pirri, G. Belcredi, and C. Rattaro, "Implementation of a low-cost ais transmitter based on sdr," in *Proceedings of the 2024 Latin America Networking Conference*, ser. LANC '24. Association for Computing Machinery, 2024, p. 10–17.

[36] "CTFd," https://ctfd.io/.

[37] M. de los Ángeles Orfila, "La facultad de ingeniería bloque a bloque: estudiantes la recrean en minecraft," *El País*, September 2021. [Online]. Available: https://www.elpais.com.uy/vida-actual/la-facultad-de-ingenieria-bloque-a-bloque-estudiantes-la-recrean-en-minecraft

[38] Y. LeCun, L. Bottou, Y. Bengio, and P. Haffner, "Gradient-based learning applied to document recognition," *Proceedings of the IEEE*, vol. 86, no. 11, pp. 2278–2324, 1998.

[39] C. Sagan and A. Druyan, *Pale Blue Dot: A Vision of the Human Future in Space*. Random House Publishing Group, 2011.

[40] "*The Sounds of Earth Record Cover.*" https://commons.wikimedia.org/w/index.php?curid=137443.

[41] The Staff at the National Astronomy and Ionosphere Center, "The Arecibo message of November, 1974," *Icarus*, vol. 26, no. 4, pp. 462–466, Dec. 1975. [Online]. Available: https://www.sciencedirect.com/science/article/pii/0019103575901165

[42] R. García, A. Armendariz Voelker, J. Umpierrez, and C. Rattaro, "Code huntresses: Promoting gender equity in icts," in *Proceedings of the XV Congress of Latin American Women in Computing 2023 (LAWCC 2023) co-located with XLIX Latin American Computer Conference (CLEI 2023), La Paz, Bolivia, 18-19 oct. 2023, pp. 44-55.* CEUR Workshop Proceedings, 2023.

[43] Ron Economos., "*gr-paint*," GitHub Repository https://github.com/drmpeg/gr-paint, 2021.