Building a Radio Community across Students, Industry and Enthusiasts with Capture the Flag

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***Abstract*—We present a communications-themed Capture the Flag (CTF) tournament, featuring both virtual and in-person formats. In the virtual edition we post online several challenges containing a signal recording and an accompanying story. Registered teams analyze the signal and try to unveil a hidden message, which upon submission earns them points. The in-person variant is a treasure hunt, where hints are provided by signals obtained from any smartphone; e.g. bluetooth or audio. We share pivotal lessons learned in our four years' experience and highlight the role of these recreational activities in fostering community engagement and promoting the dissemination of the discipline.**

***Index Terms*—Software Defined Radio, Telecommunications, Tournament, Problem-based Learning**

I. Introduction

For more than 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. 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 five years [3]. This initiative, coupled with broader developments like the "5G race" and the controversial restrictions on Huawei in various Western nations, 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 [4], [5].

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 (see https://idm.uy/), so that even if participants may already be ECE students, prospective students or their families are also exposed.

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).

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 [6], [7], such as GNU Radio [8], 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).

The in-person version is targeted to latter years' high-school students. In this case, the competition takes the form of a short treasure hunt, where hints to the next "treasure" are provided by live signals received by any smartphone (e.g. bluetooth). This way unprepared attendants can easily participate. Being co-located with another event, the hunt follows a trail that engages participants to visit the exhibit all while interacting with different radio signals.

We have organized four annual editions of the virtual CTF with over one hundred competitors stemming from academia,

industry and enthusiasts in general. The in-person edition have included tens of participants of all ages. We are convinced that this kind of recreational activities fosters a sense of community around a subject that may at first impress as too technical. The next section presents SDR, as it is the core technology in our CTF. The rest of the article then discusses lessons learned from this experience, as well as presenting some of the challenges and interesting variants for both versions. 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 (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. That is to say, multiplying the passband signal by a local oscillator, analog filtering, amplifying and sampling are the only operations where hardware is involved, and the resulting complex discrete signal, commonly referred to as IQ (In-phase and Quadrature), is then processed 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 [9], HackRF [10] and RTL-SDR [11] 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 [12], 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) [13], decoding the signal of certain imagery satellites [14] or even setting up a complete cellular network [15]. 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 [8], an open-source framework where the complete processing chain is represented by a series of interconnected blocks, forming a so-called *flowgraph*. Each of these blocks performs a well-defined functionality on the data flow (e.g. filtering, forward error correction, 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 [16], some of which implement complete systems such as Digital TV [17] or LoRa [18].

In the virtual CTF, the signals provided to the participants are generated by some of these tools, typically in the form of a stereo WAV file where each channel (left and right) corresponds to the real and imaginary part of the IQ samples. Although we use a sampling rate that is much larger than what is generally used in audio (in order to accommodate the signal's bandwidth), this format has the advantage of being readable by several software tools, including GNU Radio among many others.

Naturally, in order to decode the provided signals, teams are expected to have certain skills in SDR. Depending on the challenge's complexity, this could range from basic tasks like demodulating an AM radio or the RDS of a FM broadcast, to more advanced ones such as installing software capable of demodulating a digital TV signal and configuring it correctly. How to approach each challenge is aided by the accompanying story, which serves as a clue of which technology is used in that particular recording.

Key to the success of the virtual CTF is thus to have a critical mass of people knowledgeable in SDR. Our University has for some years now included SDR projects in several of the courses in the ECE curriculum [6], [19], [20]. These courses range from the first year (where basic digital communications are overviewed) to the last (where a complete SDR-based transceiver is implemented). This 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.

III. 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.

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. 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 point 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 [21] in one of our local servers.

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 now introduce three 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 a more complex challenge, also produced in a 2-stages story. Finally, in this year's edition, 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.

B. Challenges

1) The origin: This is a simple challenge aiming to encourage 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 [22]. 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, ravels about 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, where we provide a pcap file 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.

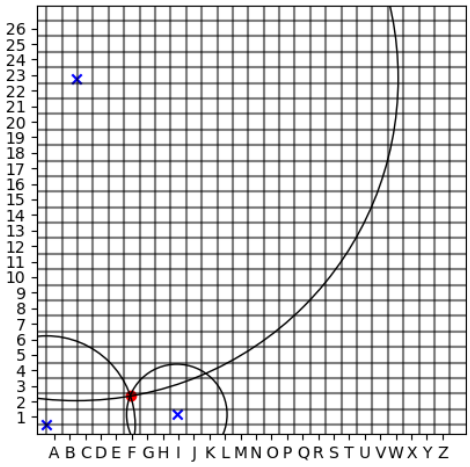

Fig. 1. Map with the solution of the *Search & Rescue* challenge: the flag is the grid element of the intersecting circles representing the location of the lost submarine.

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 corresponds each reception. 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. 1. 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 Code Division Multiple Access (CDMA) scheme with the GPS

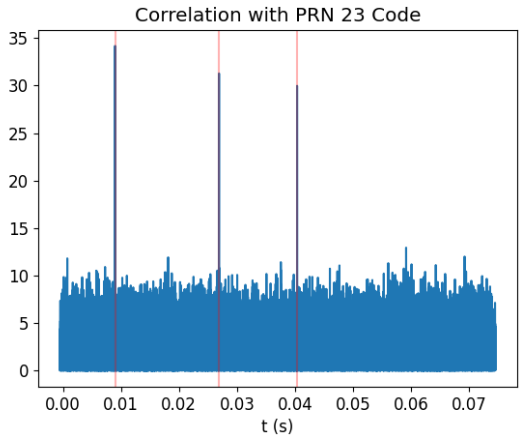

Fig. 2. The cross-correlation between the recorded signal and the PRN 23 Code can be used to solve the ranging problem in the challenge *Buried in Noise*.

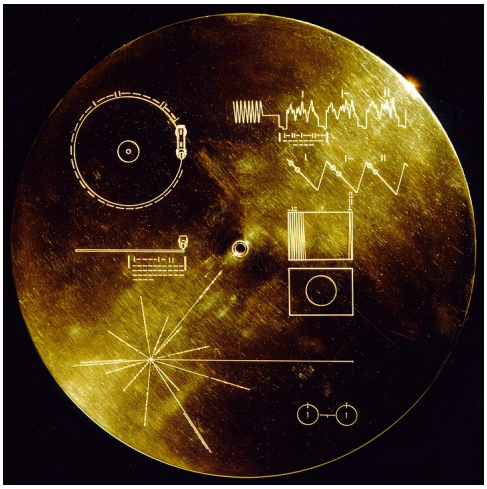

Fig. 3. The Voyager golden record containing sounds and images from the Earth [24].

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. 2). Maybe without knowingly the participants recreate the very basics of the mechanism by which the GNSS navigation works.

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* [23] 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. 3 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.

4) 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 5500 years. These inscriptions belonged to the Harappan or Indus civilization and are thought to be undecipherable as they belong to a dead language, unlike ancient Egyptian, for which 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, lay 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

C. Evaluation and Discussion

The number of participants have shown an increasing tendency over the years, starting with 18 in 2020, 36 the next, 29 en 2022 and 35 last year. In order to receive feedback, around a week after the event we organize a so-called "after-CTF", a social gathering where we discuss the challenges with the participants. This also increases the sense of community and motivates them to enroll the next year.

The evaluation that follows is based on conversations in these events, as well as on a small anonymous poll we have conducted earlier this year. In terms of demography, most of the participants are students from the latter years in either electrical or telecommunications engineering (i.e. around 25 years old), although some come from computer science or even mechanics, and a non-negligible proportion are professionals. Once they play a CTF, they generally enroll the following year. Finally, and regarding time spent by the participants, more than half have declared to have dedicated over 4 hours.

Quiet interestingly, even participants that are professionals in the field mentioned that they have learned something from the CTF. In this sense, including some challenges from other, although related, fields (such as machine learning) has been overwhelmingly well received. The accompanying stories have also been repeatedly mentioned as a great motivation to play the CTF, both the humorous and the more historical ones. We remark specially that these stories also have to provide specific clues on how to approach the challenge, else they will prove a frustration and impact negatively on the participants' engagement. In this sense, it has also been repeatedly mentioned that the existence of some "basic" challenges, such as *The Origin*

we described before, is also highly motivating as they start to play.

IV. In-person CTF

As we mentioned before, and is apparent from the previous challenges, the virtual CTF requires a technical background (at least a basic knowledge on topics such as frequency analysis or signal processing), and is clearly not accessible to, for instance, high-school students. The proposed challenges were meant to be solved either by university students or by professionals and amateurs in the area. After a couple of years of organizing successful virtual editions of the CTF, it became apparent that we needed to extend 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 in them. In fact, the more technical version has been re-used and adapted for other general public activities in our University [20].

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, a process that repeats 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 held for the first time in 2022 and there were four stations in the campus. In each of them, a modulated signal with an encoded message was transmitted using GNU Radio. The messages consisted of audio recordings modulated using AM, images painting the RF spectrum (by using a contributed module of GNU Radio called *gr-paint* [25]), Morse code modulated in Continuous Wave, and an FM transmission. The complexity of the challenges was mostly in receiving the signals and in finding the place of the next station (recall that several participants had never actually used an SDR before and were not University students). Participants were not only allowed to search information on the Internet, but encouraged to do so, in hopes that they would learn more about the topics covered.

A total of 12 teams took part in this first edition. Although the goals of involving more people and creating fun challenges were achieved, several points for improvement were identified. The game was not yet simple enough and it lasted longer than the anticipated 20-30 minutes. The stations were far away from each other, therefore making it hard to find lost participants and check that the transmitters were still working. But maybe most importantly, it was difficult for high-school or freshmen students to use and operate effectively an SDR (and the corresponding software). A one-hour crash course was provided before the event to the enrolled participants, but this presented some complications. The most important one was that if during the event someone wanted to participate they could not, since they had not attended the crash course. Furthermore, and naturally, logistics were also complicated by the fact that we had to lend a laptop and an SDR to each participating team, and thus had to schedule each one a certain time-slot.

B. Smartphone-based in-person CTF

The second edition of the in-person CTF was celebrated in 2023, and the objective was to alleviate some of the difficulties we faced in the previous version. Notably, we intended that all people visiting the event were be able to participate in the in-person CTF. Thus, we designed a new treasure hunt, but this time we only required a smartphone to participate.

Given that the only required material was a phone with Internet access, there was no need for participants to register themselves for the competition beforehand. This resulted in many more people taking part, where even kids showed interest in participating and successfully made it through the competition. A total of 43 teams joined the search, more than tripling the participation from the previous year.

Challenges were also further simplified, where this time the accompanying text of each challenge provided clues on both the next station's location (this time a specific part of the event), as well as to what interface of the smartphone should be used to receive the flag. For instance, we installed another cellphone whose Bluetooth device name provided the flag and constantly announced itself. Another station was simply a Wi-Fi AP whose SSID was the flag. Or another one was a speaker producing a sound whose spectrum spelled out the flag. Several other possibilities exists, such as the GPS or NFC, which we will explore in the following editions.

We are confident that this second version accomplishes several objectives. It not only enhances the visibility of the ECE discipline among prospective students and the general public but also serves as an introductory activity for high school students to engage with our University. Additionally, it highlights potential areas of study for their future while reinforcing the idea that such challenges can be valuable learning experiences.

V. 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 form as a treasure hunt, 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, we envision that garnering endorsements from other universities or involving them in the organization will lead to an even more expansive SDR community.

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