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Configuring an Intelligent Reflecting Surface for Wireless Communications

Highlights from the 2021 IEEE Signal Processing Cup student competition

The shape of a surface determines how it interacts with wireless radio-frequency signals. Taking a homogenous metal plate as an example, we can bend and rotate it in different ways to make the incident wireless signal become diffusely or specularly reflected in the desired manner. The same effect can be electronically achieved by using an intelligent reflecting surface (IRS), which is a 2D array of metamaterials. By creating heterogeneous impedance variations over the surface, we can synthesize the reflection of a bent and rotated surface but without any mechanical manipulations.

The IRS technology is currently being investigated as a prospective component of 6G mobile networks, with the purpose of directing wireless signals from a transmitter toward a receiver to raise the signal strength and, thereby, communication performance. To integrate an IRS into contemporary wireless technology and make the required algorithmic and protocol changes, a joint effort among electromagnetic [1], communication [2], [3], and signal processing [4] experts is needed.

The signal processing side of the IRS technology was considered in the 2021 IEEE Signal Processing Cup (SP Cup). The SP Cup is a competition where teams of undergraduate students tackle challenges at the scientific forefront. Each team should include one faculty member as an advisor, at most one Ph.D. student or postdoctoral researcher as a mentor, and 3–10 undergraduate students (enrolled as bachelor's or master's degree students). They participate in an open competition with a clearly measurable performance goal. The top three teams are then selected to present their work at the final stage of the competition at ICASSP, where additional aspects of the works are considered in the evaluation.

The SP Cup is a competition where teams of undergraduate students tackle challenges at the scientific forefront.

ICASSP 2021 was supposed to be organized in Toronto, Canada, but the COVID-19 pandemic turned it into a virtual event. This article provides an overview of the IEEE SP Cup 2021, including the competition setup, teams, technical approaches, and statistics.

Signal processing for IRS configuration

The competition considered a communication setup where a wireless base station was deployed to serve several different user devices that are all located in the same large room. A high-level illustration of this use case is provided in Figure 1, where there are plenty of objects between the base station and the area where the prospective users reside. The radio waves interact with these objects in a way that is traditionally uncontrollable. In the figure, the direct path between the base station and user is blocked by a wall and, thus, highly attenuated, leading to a low signal-to-noise ratio. To improve the propagation conditions, an IRS has been deployed at a fixed location on a wall. Its location is carefully selected so that it has an unobstructed line-of-sight (LOS) path to the base station and a good chance of also having an LOS to users.

The IRS consists of $N = 4{,}096$ controllable elements (also known as *meta-atoms* or *unit cells* in the electromagnetic literature), which are passive in the sense that they will (diffusely) reflect radio waves that are reaching them from the base station but will not process or amplify the signals. However, each IRS element has a tunable impedance, which is controlled using a switch that has two states in the considered setup. By changing the switch, the reflection coefficient can be changed, which implies that the amplitude and phase shift of the reflected signal are modified. Although the IRS has the ability to modify the impedance pattern over its surface, it contains only passive components, and this implies there is no added thermal noise.

The general principle of IRS-aided communication is to set the switches in such a way that the signals from the N elements are constructively combined at the user location. In other words, the diffusely reflected signals are phase-shifted so that constructive interference

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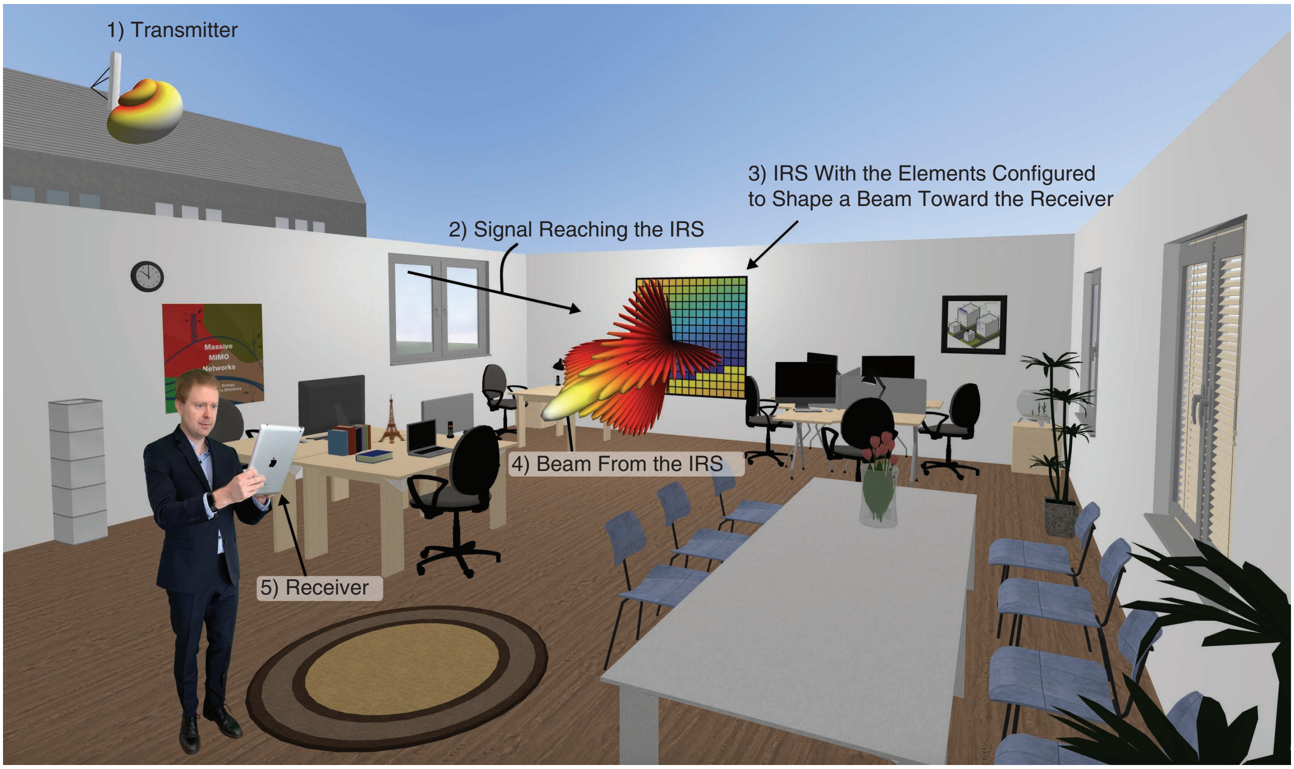

FIGURE 1. A typical use case of an IRS, where it receives a signal from a transmitting base station and reradiates it focused toward the receiving user. To focus the beam in the right direction, the IRS must be configured properly. (Source: [3]; used with permission.)

occurs in the direction of the receiver, which results in the beam shown in Figure 1. This procedure resembles classic analog transmit beamforming [5], but it differs in the sense that the IRS is not generating the signal but just adapts its electrical properties to make the reflected signal take the form of a beam in the desired direction. This implies that tools from array signal processing can be utilized when modeling and optimizing the operation [3].

The main challenge is to select which IRS configuration to utilize for each given user. The input to such a selection algorithm is represented by the measurements of the received signals at the user for different IRS configurations. The IRS cannot make any measurements on its own since it is passive; it can only receive a control signal (from the base station or user) that tells it which configuration to use. Before that, it can circle through a preselected set of configurations so the system can estimate their respective suitabilities.

Figure 2 illustrates this procedure, where the user devices save the received signals for different configurations, process them to extract useful information, and then decide on which IRS configuration to utilize. There are $2^N = 2^{4,096}$ possible configurations in the setup considered in the SP Cup, which is, practically speaking, infinitely large. Hence, an exhaustive search is hopeless, both from the measurement and computational perspectives.

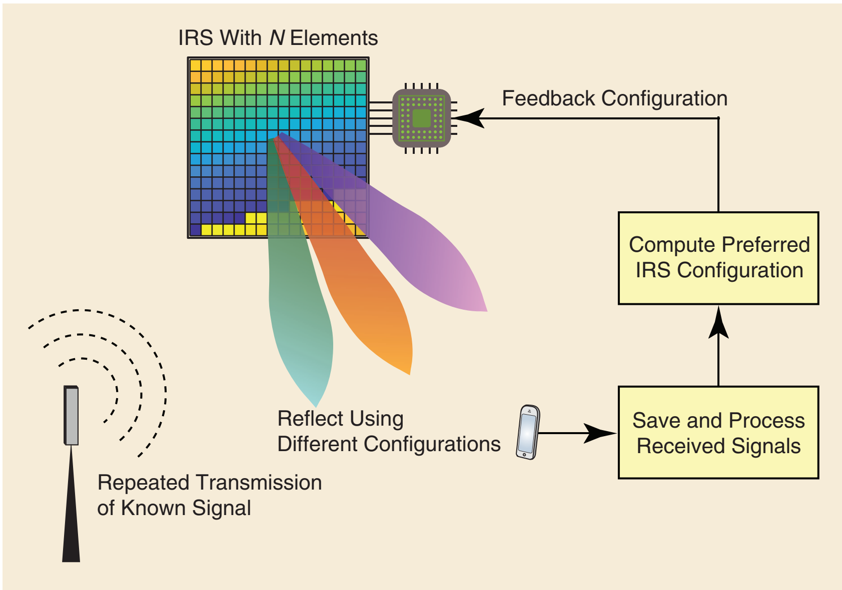

FIGURE 2. One way to identify a suitable IRS configuration is to transmit a known signal multiple times and let the IRS reflect it using different configurations. The receiver measures the signals and feeds them to an algorithm that selects the IRS configuration that maximizes the data rate.

The goal of the SP Cup was to design a signal processing algorithm that selects a good IRS configuration based on measurements made at different user locations. It is plausible to design such algorithms based on a number of measurements that grows linearly with N rather than exponentially since the number of unknown channel parameters is proportional to N. Mathematical details can be found in [6].

The students had to be creative when designing their approaches and were truly developing novel algorithms.

Task in the SP Cup 2021

The goal of the competition was to configure the IRS to maximize the average data rates (in bit/s) that can be delivered to users at 50 different locations. For each user location, students were given a data set containing a noisy received signal obtained when repeating the same predefined pilot signal while switching between N predefined IRS configurations. Moreover, the competing students were given one extra data set that could be used to extract further properties about the wireless propagation environment and IRS hardware. For every user location, each team should obtain one carefully selected IRS configuration.

Most of the 50 users had LOS propagation conditions, which make the configurations somewhat easier because the IRS should turn its reflected signal into a focused beam pointing in the corresponding angular direction. However, a few of them also had non-LOS conditions, which make the IRS configuration more challenging since it must take multiple scattered paths into account. To encourage the students to design an algorithm that can also handle this situation well, the data rates of those users were doubled when computing the (weighted) average data rate.

Since the IRS is an emerging technology with limited experimental equipment, the data set was generated synthetically in MATLAB, but the setup captured many practical aspects of wave propagation, such as frequency-selective fading, signaling based on orthogonal frequency-division multiplexing, and mutual coupling between closely spaced elements. Further technical details about the simulation environment are given in [6], which also contains a link to the entire data set and complete MATLAB scripts. It is worth noting that experimental results for a similar practical setup can be found in [7].

To prevent the direct use of algorithms from prior work, the problem setup featured four carefully crafted properties:

- Frequency-selective fading, which had been considered in only a handful of papers at the time (e.g., [3] and [8]–[10]), was used.
- Each element of the IRS could be configured into only two discrete states for which the reflected signal component is either phase-shifted by +90° or –90°, while most prior literature considered the case of continuous phase shifts.
- Hardware imperfections were modeled using unbalanced reflection amplitudes between the two states and mutual coupling.
- There were too few measurements to estimate all channel parameters, even in the absence of hardware imperfections.

The last two properties were not explicitly stated in the problem description; thus, the students had to discover them on their own. In summary, the students had to be creative when designing their approaches and were truly developing novel algorithms.

To support the competing teams in their efforts, two webinars were organized and then uploaded to the YouTube channel *Wireless Future*. The problem formulations were also discussed in a classroom at Piazza.

Results from the open competition

An important part of the competition was that the teams could not compute the exact average data rates but only try to estimate them and use the approximations when tuning their algorithms. The open competition was organized in two steps. Each team first submitted a preliminary solution, which was used to generate a leaderboard with the exact data rates. The teams then had a few weeks to revise their methods and submit their final solutions. A total of 37 teams submitted preliminary solutions, of which 30 teams submitted their revised solutions for final evaluation. The final results are given in Table 1 and reveal that it was a tight competition, with less than 1% performance difference between the highest value and the team in place 10.

Figure 3 gives a further perspective on this by showing the rates achieved by

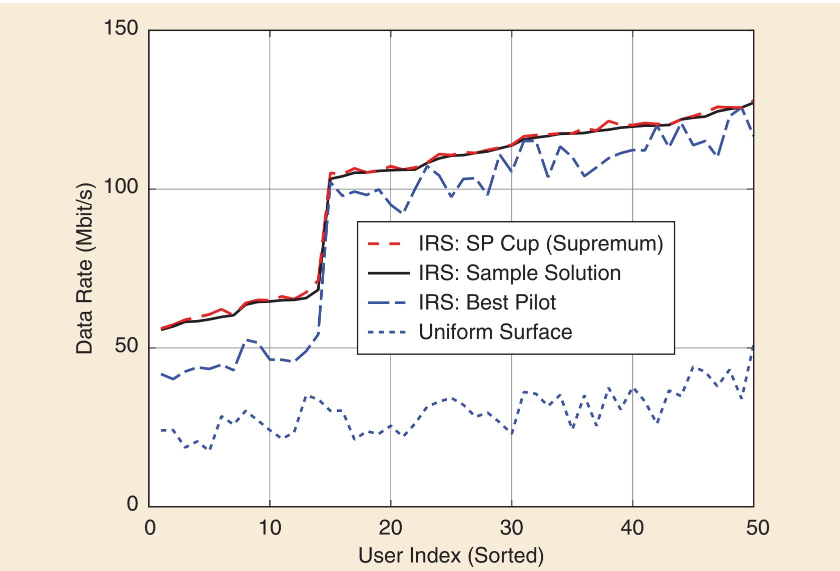

FIGURE 3. The data rates achieved by the best SP Cup results, with the sample solution from [6] and two other baselines.

the 50 users, ordered based on increasing rates obtained by the sample solution in [6]. The solid line shows the sample solution, while the dashed red line is the best result among all of the teams, which beats the sample solution for every user. Two additional baselines are shown: one obtained by using the best configuration among the N ones used during the pilot-based measurements and one obtained by a uniform surface (i.e., using the same configuration in each IRS element).

These curves reveal two important things. First, an IRS can greatly improve the data rates compared to a static uniform surface, such as a metal plate. Second, to find a competitive solution, the students had to discover an IRS configuration that was not among those that were used in the measurement phase.

Final competition

The three highest scoring teams in Table 1 were selected as finalists and invited to an online session that was organized during ICASSP 2021. At this stage, the theory behind the algorithms was important, and each team was invited to prepare a video about it. The teams then answered questions from a jury, which made the final decision based on the technical quality, presentation quality, and students' ability to answer questions about their solutions. The final winner was T-Cubed from the University of Moratuwa, Sri Lanka (Figure 4). The first runner-up was Team AGH from the AGH University of Science and Technology (Figure 5), Poland, and the second runner-up was UnBounded from the University of Brasilia, Brazil (Figure 6).

Highlights of technical approaches

A common factor among the successful teams was that they first attempted to estimate the propagation channels using a mix of classical estimation methodology and their creativeness. Since there were more unknowns than observations, a structured procedure for dimension reduction was needed. Several teams identified patterns in the data that revealed that the 4,096 elements were geometrically organized as a square array with 64 × 64 elements. This was a correction conclusion.

Moreover, they identified that most of the variability in the propagation channels happened in the azimuth domain, while

Table 1. The results from the 30 teams in the open competition.

Team	Metric (Mbit/s)
Team AGH	118.31
UnBounded	118.28
T-Cubed	117.82
WiseCom	117.81
Hive	117.76
SIPL Team	117.73
Wireless-Shark	117.70
JKLG	117.67
hUMAns at RISk	117.59
Meta-Darpan	117.58
Unlimited Data	117.32
IITGSARR	116.97
Hydra	116.25
RISE@IITK	116.00
MBNRG_IUST	115.89
Team Centura	115.86
UBCO Team	115.85
SAMARITAN	115.76
SACHSOYAB	115.09
ADSP	114.98
DAIA	114.38
vlsilab	113.79
TCE Yukthi	113.59
University Carlos III of Madrid	113.30
The A Team	108.49
E-WALL	103.55
ku_wireless_research_group	89.90
DEUSP	61.02
SEUSL Signal Champs	56.93
IIITG_CREATORS	35.30

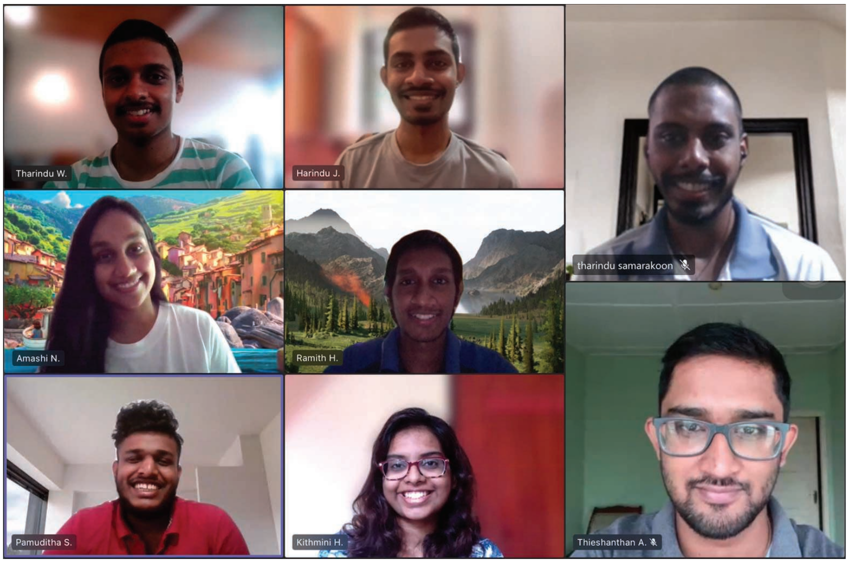

FIGURE 4. The winning team, T-Cubed, consisted of Tharindu Wickremasinghe, Harindu Jayarathne, Tharindu Samarakoon, Amashi Niwarthana, Ramith Hettiarachchi, Pamuditha Somarathne, Kithmini Herath, and Thieshanthan Arulmolivarman under the supervision of Dr. Prathapasinghe Dharmawansa at the University of Moratuwa, Sri Lanka.

the channel coefficients within each vertical column of the IRS were approximately the same. By making use of this property, the number of unknown channel parameters could be reduced from 4,096 + 1 to 64 + 1, where the + 1 term represents the uncontrollable direct path from the transmitter to the receiver.

The next step in the solution was to devise an algorithm that takes the estimated channel coefficients and selects an appropriate IRS configuration. This is a combinatorial task with $2^{4,096}$ possible solutions; thus, many of the teams made use of evolutionary algorithms, such as the genetic algorithm, to search for good configurations in a structured yet heuristic manner. Detailed descriptions of the solutions created by the three finalists can be found in their respective videos on the YouTube channel *Wireless Future*. The sample solution in [6] captures everything except the final evolutionary step.

The supporting materials shared by the organizers were beneficial to learn new concepts and form a solution to the task.

SP Cup 2021 statistics

A total of 59 teams registered for the competition from all around the world. The 30 teams that submitted final results were from 13 countries: Brazil, Chile, China, Greece, India, Iran, Israel, Italy, Poland, Spain, Sri Lanka, Turkey, and the United States.

Since its inception, the SP Cup has received generous support from MathWorks, the maker of MATLAB, which was also the software tool used to generate the data set. MathWorks kindly provided funding support to the SP Cup and free MATLAB licenses to competing students.

Participants' feedback

In this section, two of the finalist teams provide their perspectives on the SP Cup 2021.

T-Cubed

When the SP Cup 2021 was announced, we formed our team composed of second- and third-year undergraduates from the Department of Electronic and Telecommunication Engineering, University of Moratuwa. Although we did not have a clear conceptual grasp of IRSs, we decided to take the challenge, motivated by the fact that we had a good grounding in the basics needed. As expected, it was a steep learning curve to get to the details in the area. There were strict lockdowns in the country due to COVID-19 in this period, and we had to improvise our ways of collaboration, relying on virtual platforms. We set about it methodically, dividing the work and documenting it, thus moving efficiently toward the goal. This also enabled us to utilize the expertise of our supervisor effectively during this project.

Amid the divergent and challenging academic schedules of our second- and third-year group members, we helped each other keep up the momentum and bring in diverse ideas. The supporting materials shared by the organizers were beneficial to learn new concepts and form a solution to the task.

The nature of the problem was to configure the behavior of an IRS to maximize the data rate for different users. Our strategy was to maximize the data rate and reduce the latency as much as possible so that it is suitable for practical applications. During the preliminary submission, we submitted an unoptimized solution to get an idea about the data rate it achieved, and we were placed sixth in the ranking. We continued our work to formulate an elegant solution

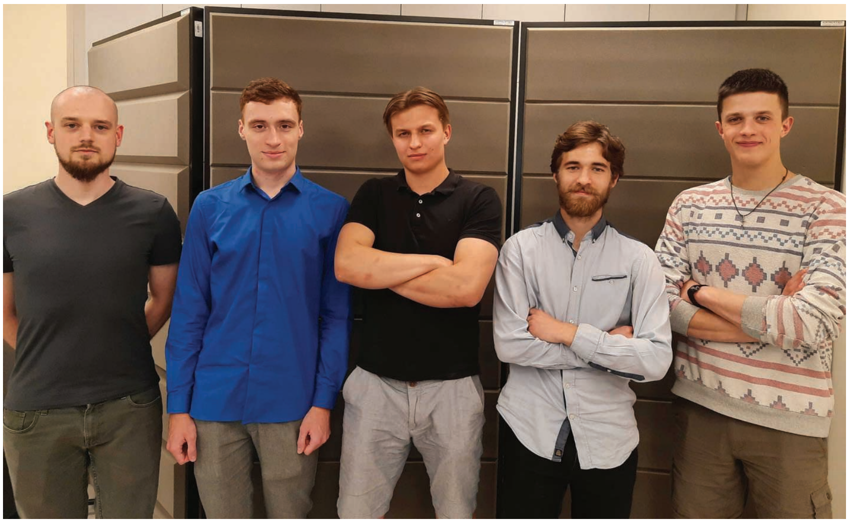

FIGURE 5. The first runner-up, Team AGH, consisted of (from left) Szymon Woźniak (tutor), Michał Antos, Piotr Radecki, Aleksander Strzeboński, and Mateusz Wojtulewicz under the supervision of Prof. Konrad Kowalczyk at the AGH University of Science and Technology, Poland.

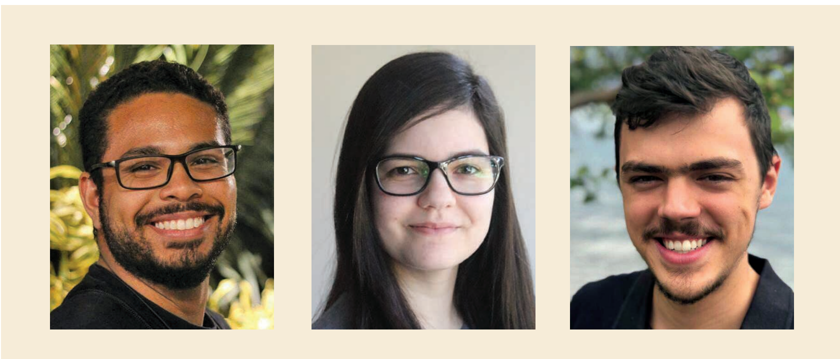

FIGURE 6. The second runner-up, UnBounded, consisted of (from left) Gustavo Viana Penido, Hiandra Tomasi, and Rodrigo Fischer under the supervision of Prof. Marcelo Menezes de Carvalho at the University of Brasilia, Brazil.

that exploited the geometry of the IRS, and we submitted it as our final solution. This paved the way for us to compete in the grand finale at ICASSP 2021, which was a great experience. Working on the competition task opened new horizons to learn more about vital aspects of wireless communication, such as channel modeling, statistical estimation, and optimization. It was a great opportunity to apply fundamentals in solving a real-world problem.

Looking back, we are very glad that we were able to spend several months collaborating remotely under the guidance of our supervisor to come up with a solution to this exciting problem. We thank Prof. Emil Björnson and the organizers, particularly the IEEE Signal Processing Society (SPS), for their dedication and contribution to organizing this highly challenging competition, which inspired undergraduates from all over the world to solve useful problems through signal processing.

Team UnBounded

Participating in the 2021 SP Cup was a great opportunity for us, as undergraduate students, to dive deeper into a topic ourselves and work together to find a good solution for the problem. We think that competitions like this encourage students to engage in research activities and also show them that research can be exciting and fun. Also, the 2021 SP Cup was a gateway for us to participate in the 2021 ICASSP, which was very rewarding. We all thank IEEE and Prof. Björnson for the opportunity to dive into IRSs: we found this topic extremely challenging and interesting.

The whole competition was very thrilling: we felt like detectives trying to uncover a mystery. Working with limited data led us to devise clever ways of processing them to collect information about the channel model. Also, the huge number of possible configurations for reflective surfaces pushed us to develop artificial intelligence-based algorithms to choose the best solution for each user.

Acknowledgments

As the organizers of the SP Cup 2021, we would like to thank all of the people who took part in this competition: the participating teams; the additional jury members (Erik G. Larsson and Honglei Chen); the SPS Membership Board for its full support; Esha Shah, who organized a dedicated webinar on MATLAB; and MathWorks for its sponsorship.

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