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Location Signatures That You Don't See

Highlights from the IEEE Signal Processing Cup 2016 Student Competition

When thinking about using technologies to find one's location, many of us may consider satellite-based global navigation systems, such as the U.S. global positioning system (GPS). Smartphones today use GPS type signals and cellular network signals to determine the phone user's current location and offer a broad range of location-related services. But when there was no such real-time connection and signal to analyze, for example, having only a piece of video or voice recording as an evidence of a news story or from child exploitation investigations (which have become an important global issue being addressed by the United Nation's UNICEF organization), are we out of luck?

Fortunately, some very weak traces about the location may be "imprinted" to become part of the sound or visual signals during the sensing process [1]. These traces cannot easily be seen or heard by a human, but it is possible to extract them using signal processing techniques. The contribution of these location signatures–perhaps less foreseeable to a layman—come from the variations in electric power supplies [2]. Thanks to information forensics research in the last decade, the frequency variations, known as *electric network frequency* (*ENF*) signals, are being extracted and exploited to answer a range of forensic questions. Interested readers may refer to publications such as [3] and [4] and the references cited therein.

Exploring location information of these ENF signals was the topic area of this year's IEEE Signal Processing Cup (SP Cup) competition. The SP Cup is an undergraduate competition organized by the IEEE Signal Processing Society (SPS) in which undergraduate students work in teams to tackle a real-life signal processing problem. Launched in 2014, the SP Cup competition has been held annually, and 2016 is the third edition. To join the SP Cup competition, undergraduate students are required to form a team. Each team is composed of one faculty member to advise the team members, up to one graduate student to assist the supervisor in mentoring the team, and three to ten undergraduate students. Three top teams are selected from the initial round of competition and provided travel grants to participate in the final competition at the 2016 IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP). The final results are shown in "Winners of the SP Cup 2016."

> **"Everyone has gained knowledge or skills in different aspects. The SP Cup is a catalyst."**

This article provides an overview of the technical tasks and highlights representative approaches and participants' reflections.

Location signatures in power and media

As suggested by its name, ENF is the frequency of a power distribution grid. The nominal value of ENF is 60 Hz in North America and 50 Hz in most other parts of the world. ENF typically does not stay constant at its nominal value but rather fluctuates around it due to load changes across the grid and the control mechanisms that adjust the amount of power generation to stabilize the frequency changes. We refer to the changing values of the ENF over time as an *ENF signal*. An example of an ENF signal can be seen in Figure 1.

What makes the ENF particularly relevant to multimedia forensics is that audio or video recordings captured in areas where there is electrical activity, such as our offices and living rooms, may capture the ENF variations. In audio, this can be from the ambient power hum, and in video, this is due to the near-invisible flickering of electrical lighting. As the exact variations of ENF appear to be random and difficult to predict, the embedded ENF traces can serve as an intrinsic fingerprint that can be used for a number of forensic applications. In recent years, it has been shown that the embedded ENF traces can be used as a timestamp of media recordings as well as an indicator as to whether or not the media recording was tampered with [3], [5].

For the 2016 SP Cup, the competition topic was shaped around using ENF to identify the power grid in which a media recording was made. Upon examining ENF signals collected from different

Digital Object Identifier 10.1109/MSP.2016.2581738
Date of publication: 2 September 2016

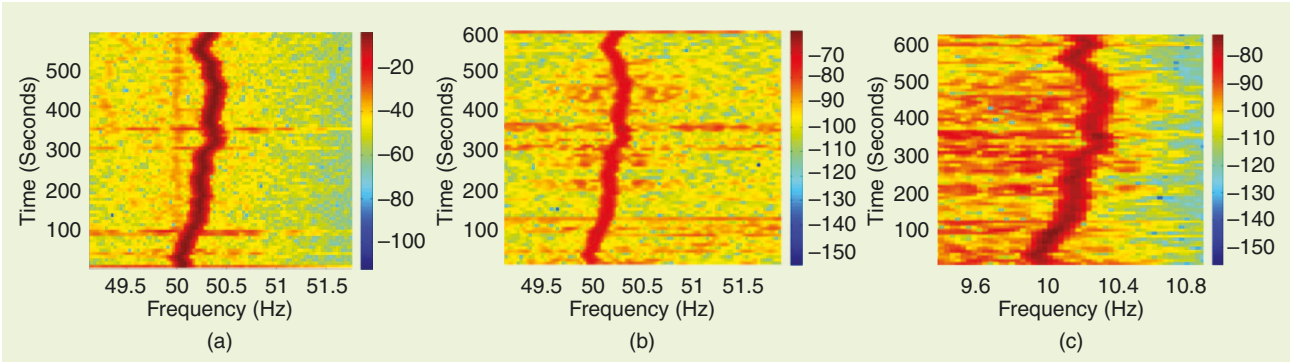

FIGURE 1. A spectrogram showing ENF signals in concurrent recordings of power main, audio and visual recording. The cross-correlation study can show similarity between media and power line reference at different time lags, where the peak suggests their temporal alignment. (a) Concurrent power-line. (b) From the audio track. (c) From the video track.

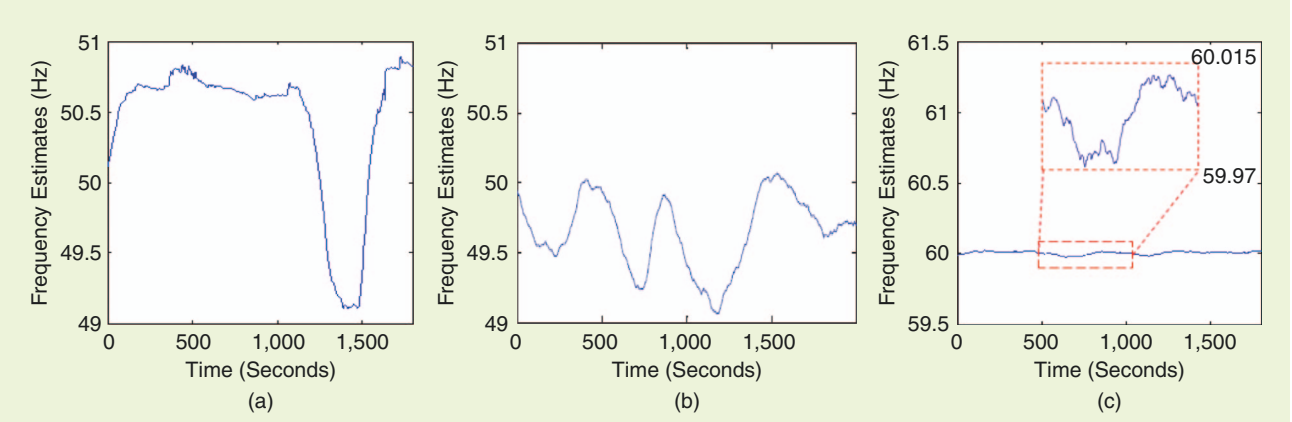

FIGURE 2. Instantaneous ENF variations over time exhibit different characteristics in grids around the world. (a) Lebanon. (b) India. (c) Eastern United States. (Figure used courtesy of [6].)

grids, one can see they differ in the nature and manner of their variations. An example is shown in Figure 2, where we can compare data from Lebanon versus India versus the United States. A machine-learning system can be constructed to learn the characteristics of the ENF signals from different grids to discriminate the grid of origin of a certain recording by examining the ENF traces embedded in it.

Tasks in SP Cup 2016

The open competition stage

The SP Cup started with an open competition stage from September 2015 to January 2016, consisting of two parts. For the first part, participants were first given recordings made in nine grids labeled A–I. Some of the recordings were audio recordings from different locations and environments, and others were power recordings. Power recordings were made using a custom-made circuit that records the power signal directly from an electric outlet fed into a digital recorder. The main part of a typical circuit for this purpose includes a step-down transformer and a voltage divider. The power recordings generally exhibit very strong ENF traces as sinusoid signals around the base frequency and have much stronger and cleaner traces than the ones seen in regular audio recordings.

The participants were asked to extract the ENF traces from the recordings and build a machine-learning system that could learn the unique characteristics of the ENF signals from different grids. To help the participants test their algorithms and systems and refine their work, they were also provided with 50 practice samples of power and audio recording, each of which was ten minutes long. A simple oracle website was set up for participants to input their predictions on this practice data set and then receive feedback on the accuracy of their predictions. During the final month of the open competition, participants were provided with the final testing data set, composed of 100 power and audio recordings of ten minutes long each. Both the practice samples and final test samples included some of the recordings from grids outside the nine grids of A–I given for training. Participants were asked to report their predictions on this testing data set as part of their submissions of the open competition. The accuracy of their results was one of the judging criteria in the choosing of the top three teams.

For the first time since the inception of the SP Cup, the competition included hardware and sensing components, which are important aspects of signal processing.

Winners of the SP Cup 2016

Grand Prize: Team Resonance_101
- Bangladesh University of Engineering and Technology, Bangladesh
- Undergraduate students: Sayeed Shafayet Chowdhury, Md Billal Hossain, Jayanta Dey, Ashraful Islam, Rakib Hyder, Md. Samzid bin Hafiz, Ratul Khan, Munif Ishad Mujib, Tauhiduzzaman Khan Himel, and Uday Saha
- Supervisor: Mohammad Ariful Haque.

Second Prize: Team Hammer Down
- Purdue University, United States
- Undergraduate students: Alexandria Moore, Xiangyu Qu, Samuel Sowell, Fangjia Zhu, Siqing Wei, Gregory Dykes, and Christopher Chow
- Supervisor: Stanley Chan
- Graduate Mentor: Benjamin Vondersaar.

Third Prize: Team Vidyut
- Multiuniversity team: Indian Institute of Technology–Madras, National Institute of Technology–Karnatak, Surathkal, and Indian Institute of Science–Bangalore
- Undergraduate students: Priyadarshini Savan Roshan, Pradyumna Byappanahalli Suresha, Aditya Gaonkar P, and Supriya Nagesh
- Supervisor: Prasanta Kumar Ghosh
- Graduate Mentor: Nisha Meenakshi.

In addition to the three overall winning teams, the SP Cup 2016 judging committee made the following special recognitions and honorable mentions.

Special Prize for Sensing Circuit System
- Team "UpatrasECE," University of Patras, Greece
- Team "The ENForcers," University of Novi Sad, Serbia

Special Recognition of Originality
- Team "Hammer Down," Purdue University, United States

Special Recognition of Young Team (student participants in their freshman or sophomore year of college)
- Team "IIT Hyderabad," Indian Institute of Tech Hyderabad

Honorable Mention for Overall Excellence
- Team "UNStoppable," University of Novi Sad, Serbia
- Team "UpatrasECE," University of Patras, Greece

Honorable Mention for High Classification Accuracy
- Team "USTC2016," University of Science and Technology of China.

Participants were asked to design and implement their own circuit to measure a power signal and extract and analyze the ENF traces. After designing the circuit, they were instructed to use it to collect recordings from the power grid in which they live and then analyze these extracted ENF signals and compare them to what they extracted from the recordings of grids A–I provided in the competition. Each team was instructed to provide approximately ten hours of collected recordings together with their analysis as part of their submission for the open competition.

Final competition

After the judging committee evaluated the submissions from the open competition, three finalist teams were chosen to advance to the final competition. Prior to attending the final event at ICASSP, the finalist teams were provided with additional training data from three new grids, which were selected from the recordings submitted in the open competition by other teams. The participants were asked to incorporate this newly acquired data into their learning systems and were allowed to further refine their systems.

The final SP Cup event was held at the ICASSP in Shanghai, China, on 20 March 2016. At the beginning of the event, the participants of the finalist teams were provided with an additional 50 ten-minute testing samples to combine with the test samples from the open competition round, for a total of 150 testing samples. After submitting the results within an hour, each team presented its work on the ENF extraction, the learning system, the sensing circuits, and the corresponding signal analysis. The final judging committee convened and selected the first-second- and third-prize winners as well as special recognitions.

Approaches to identify grid of origin

As outlined previously, one of the main goals of the SP Cup competition was to identify the grid of origin of power and audio signals containing ENF traces.

Many of the teams extracted the dominant instantaneous frequency around nominal ENF frequencies over short time windows and used the features proposed in [6] and their variations or extensions to develop a feature set for pattern analysis and classification. The basic types of features employed, shown in Figure 3, include 1) statistical features related to ENF values (mean, variance, and range), 2) features extracted from wavelet analysis of ENF signals, and 3) features based on autoregressive modeling of ENF signals. Two examples of other features proposed by participating teams are histogram-based features around ENF base and harmonic frequencies proposed by Team Hammer Down of Purdue University, United States, and features based on the extrema in the ENF signal and the rising edges that can be present developed by Team UpatrasECE of the University of Upatras, Greece.

A common strategy for pattern analysis and classification that was employed by the participating teams, particularly the three finalist teams, was to differentiate between four different types of signals: 1) power signals with 50-Hz nominal ENF, 2) power signals with 60-Hz

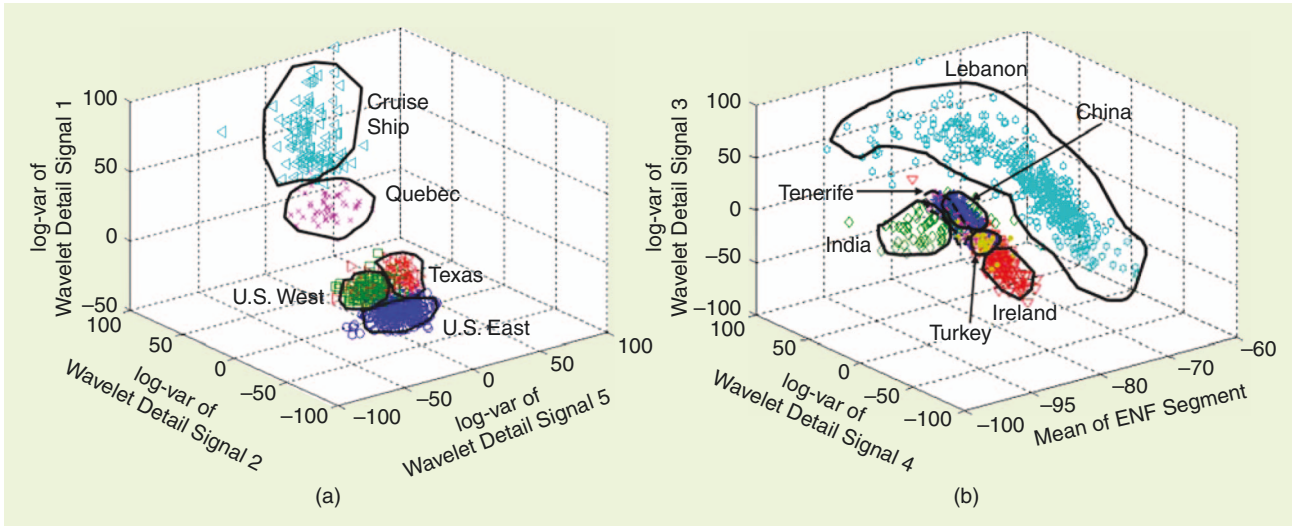

FIGURE 3. An example of features derived from ENF signals for differentiating the originating power grids.

nominal ENF, 3) audio signals with 50-Hz nominal ENF, and 4) audio signals with 60-Hz nominal ENF. While each team had their own design for the learning and classification system, their solutions all consisted of four subsystems, one dedicated to each data type. Some of these subsystems had certain variations in the way the ENF signals were extracted or utilized different discriminating features, depending on which of the four types to which the signal belonged.

The first-place winning team, Team Resonance_1011 from Bangladesh, employed two-stage support vector machine (SVM) classifiers for each data type. The first one is a one-class SVM classifier that decides if the signal belongs to a grid seen in training, and the second SVM classifier narrows down the list of possible grids on the basis of different discriminating features extracted from the embedded ENF signals. The last stage of the classification is where the testing signal is passed to a "pole-matching" classifier to reach a final decision on the grid of origin based on the minimum distance between the estimated poles of the training and testing grids.

Team Hammer Down from the United States, which took second place, carefully studied the characteristics of the signals for this problem and proposed a different method from what is available in the recent ENF literature. The team's novel method utilized a multiharmonic histogram to analyze ENF signals for identifying power grids. Team members computed ENF signals at multiple harmonic locations and extracted histograms of 1) ENF magnitudes, 2) the signal power around the ENF, 3) the noise power around the ENF, and 4) the signal-to-noise ratio of the ENF. At the classification stage, they proposed a histogram matching method with a multilayer decision rule for identification.

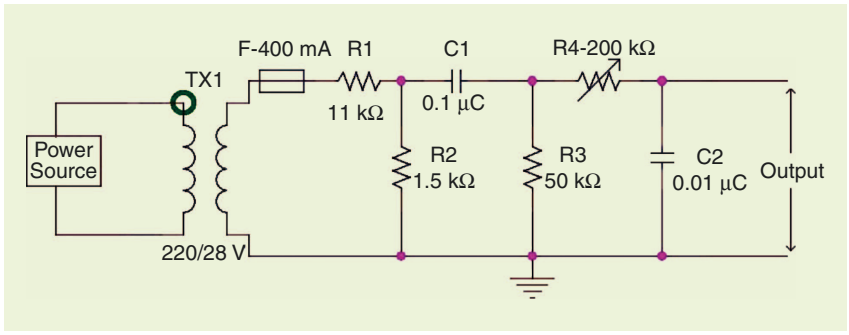

FIGURE 4. A circuit diagram from Team UpatrasECE from the University of Upatras, Greece.

Team Vidyut from India, which took third place, used a multistage SVM system where, for each input test recording, five predictions from five respective classifiers were received. To compute the confidence of a prediction, team members proposed an entropy-based measure of confidence where lower entropy means higher confidence. For audio signals, they used an additional subband classifier that captures the relative strength among the different ENF harmonic components captured by a recording. The team used custom-designed detectors to resolve conflicts in decision between their SVM and subband classifiers.

Sensing circuits

For the hardware and signal acquisition tasks in the SP Cup that aimed at bringing out the synergy of sensing, processing, and learning, nearly all participating teams built their own circuit for collecting reference power recordings from the team's respective locations. Useful references include an article in *IEEE Signal Processing Magazine* on observing the grid [7] as well as ENF-related literature [3], [5], [8]. Among the submissions received, some teams adopted the reference design, while other teams made improvements, incorporated innovative features, or employed different implementations.

Given that this is the first time the SP Cup competitions included sensing hardware design and implementation in addition to algorithmic tasks, the judging

committee reviewed this element in all entries and awarded special recognition to two teams for excellence in this task: Team UpatrasECE from Greece and Team The ENForcers from Serbia.

As shown in Figure 4, Team "UpatrasECE" thoughtfully included a glass fuse for the safety of the circuit operation. After the transformer and voltage divider that creates a reference voltage of 3 V, they included a high-pass filter to block the dc component of the measured signal and thus focused on the variation patterns and an antialiasing filter to limit the bandwidth to 500 Hz and pass on to a recording device through a 3.5-mm jack. Team "UpatrasECE" was also given an honorable mention for the overall excellence of their project.

The circuit of Team The ENForcers shown in Figure 5, included a transformer, a low-pass filter, a voltage divider, an amplifier for voltage adjustment, and an analog-to-digital (A/D) converter provided by an Arduino Uno board. An INA122P instrumentation amplifier was used in conjunction with other components for voltage adjustments so as to make the voltage compatible with the Arduino A/D converter. The sampled digital signal can be sent to a PC using Arduino's built-in serial connection for storage and analysis.

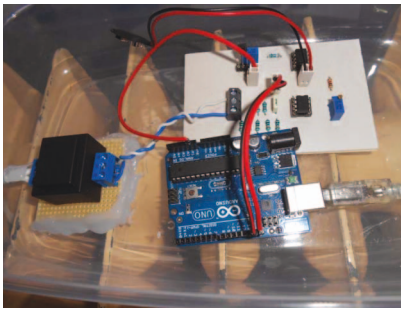

FIGURE 5. The sensing circuits by Team The ENForcers.

SP Cup 2016 statistics

SP Cup 2016 engaged participants from nearly 30 countries, covering every habitable continent. Three hundred thirty-four students from 23 countries and forming 52 teams registered for the competition, as shown in Figure 6. Among them, more than 200 students on 33 teams turned in the required submissions by the open competition deadline in January 2016. Based on team photos and other information submitted, about one quarter of the participating students were female, with many teams populated by women at a 50% or higher rate. Similar to SP Cup 2015, we once again saw strong participation from students in Asia-Pacific regions. At least two teams from Asia were in the final competition in each of the three SP Cup competitions.

To facilitate interaction and questions-and-answer sessions with participants, the organizing team used Piazza, a popular course interaction platform, as an online bulletin board to post resources and data sets as well as to address questions and engage participants. About 200 participants "enrolled" in SP Cup 2016 on Piazza and made approximately 250 contributions; in total, they have accumulated about 2,300 days of access and over 4,000 views of posts. Interested readers may access the archived Piazza site at https://piazza.com/ieee_sps/other/sp1601/home.

Since its inception, the SP Cup has received generous support from MathWorks, Inc., the maker of the popular MATLAB and Simulink platforms. MathWorks also provided funding support to the SP Cup and contributed their expertise. Each student team that registered for the SP Cup was provided complimentary software access to MATLAB and related toolboxes. The IEEE SPS welcomes continued engagement and support from industry in future SP Cup competitions. Interested supporters may contact Dr. Patrizio Campisi, director for student services, at patrizio.campisi@uniroma3.it.

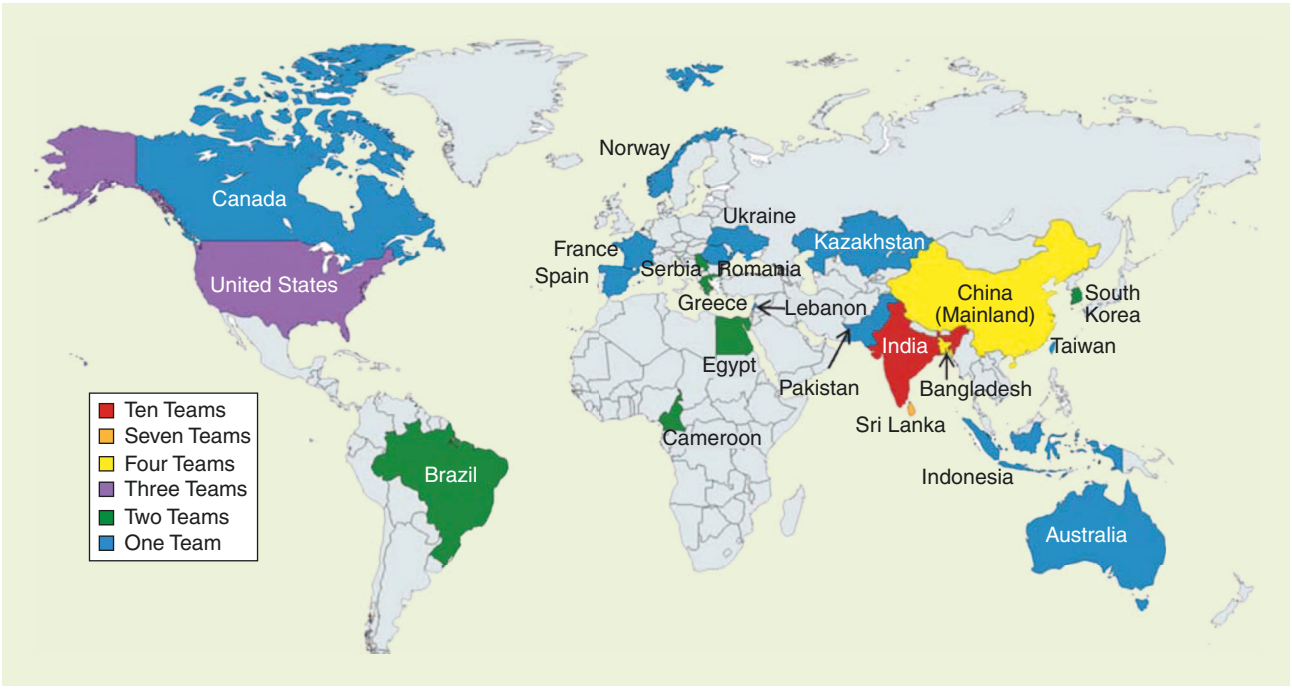

FIGURE 6. A map illustrating the number of registered teams from each participating country around the world.

FIGURE 7. Team Resonance_1011 received the grand prize.

Participants' thoughts

Whether moderating the discussions online or attending the final competition at ICASSP, we could feel the enthusiasm and dedications from the participants. Amid the understandably intense competition, one could also sense a bond, and a community formed between students of different teams through the SP Cup endeavor. Here we highlight a few words from the finalist teams as each team reflected on their journey.

Team Resonance_1011

Bangladesh University of Engineering and Technology (BUET) has had a team as a finalist in every SP Cup so far—and this year, Team Resonance_1011 (see Figure 7) received the grand prize! What an impressive performance and persistent engagement! Three students from this year's BUET team had also participated in the previous SP Cup competition and spoke enthusiastically of the rewarding experiences gained from this unique journey of learning and professional growth.

- "The SP Cup was a great learning curve indeed both times I participated. It taught us to work as a team and follow a stringent time schedule"—Sayeed Shafayet Chowdhury
- "Since this time the task was on a broader scale and we had a team comprising of ten students from different classes, we split up our work and tried to have online contacts regularly, besides having meetings with our supervisor, thus boosting our teamwork capabilities"—Billal Hossain
- "This year we had hardware tasks too... We realized it was possible to take a much simpler approach [than using complex components and boards]. … We were able to devise an extremely low cost (lower than US$5) sensing circuit that provides a perfectly adequate output."—Ratul Khan and Munif Ishad Mujib
- "The SP Cup has profound impacts on our students. Through the competition, they get to know how fundamental signal processing algorithms are used to solve a real and complicated signal processing problem. They also need to explore many advanced signal processing areas outside their text books. They become familiar with signal processing journals and conference proceedings. We have also been able to attract some good and talented students to signal processing research through their participation in the SP Cup.…Each SP Cup gave me the opportunity to work on a new signal processing application. It increases my depth and breadth of knowledge that is really helpful for teaching signal processing courses."—Mohammad Ariful Haque, faculty mentor.

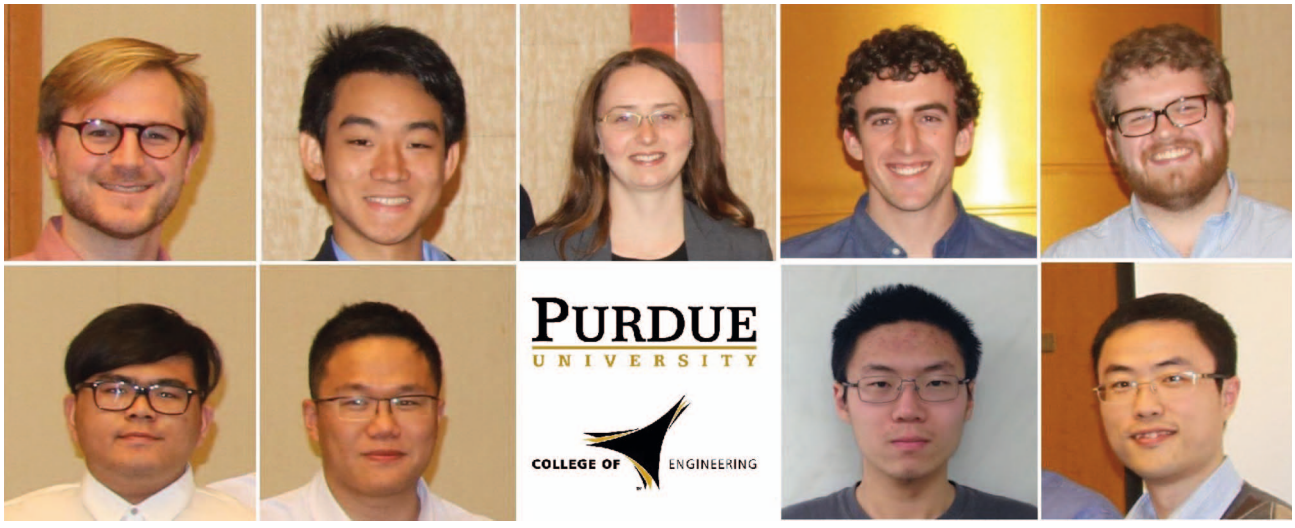

FIGURE 8. Team Hammer Down won second prize and a special recognition for original algorithm.

Team Hammer Down

Team Hammer Down from Purdue University, United States (see Figure 8), was composed of student members who were junior students (in the third year of their college career). They noted that their team was likely one of the most diversified teams in the competition, as they have students from different ethnic and cultural backgrounds with different areas of interest.

- "As a team with all members being junior students,…everyone has gained knowledge or skills in different aspects. Some of us have never done serious research.…Some of us are interested in signal processing but lack a strong motivation to go deeper… The SP Cup is a catalyst"—Team Hammer Down
- "The competition itself provided a new and challenging way to apply what I had learned in my classes. In addition to challenging myself I also learned a lot while at ICASSP. Talking to professionals in my field helped to broaden my view of electrical engineering as a whole. All in all, the SP Cup was a great experience and I recommend it to any undergraduates interested in signal processing"—Sam C. Sowell
- "I have learned a lot during the SP Cup as a junior student. It was a great chance for me to apply and practice what I have learned in the classes in a different way; instead of practicing on idealized problem sets that serve to help students understand the concepts, I was able to face some realistic signal processing problems and challenges"—Xiangyu Qu
- "Mentoring undergraduate students for the SP Cup is a challenging but rewarding experience. The difficult part is how to plan and divide the tasks, for most of the undergraduates do not have adequate background and experience. However, I am impressed by their creativity and the effort they spent on the project. They are a wonderful team. The competition provides a good opportunity for students to explore different aspects of signal processing. I personally most appreciate the integration of signal processing and circuit, for it bridges the gap between the two seemingly less correlated ends of our curriculum nowadays."—Prof. Stanley Chan, faculty mentor.

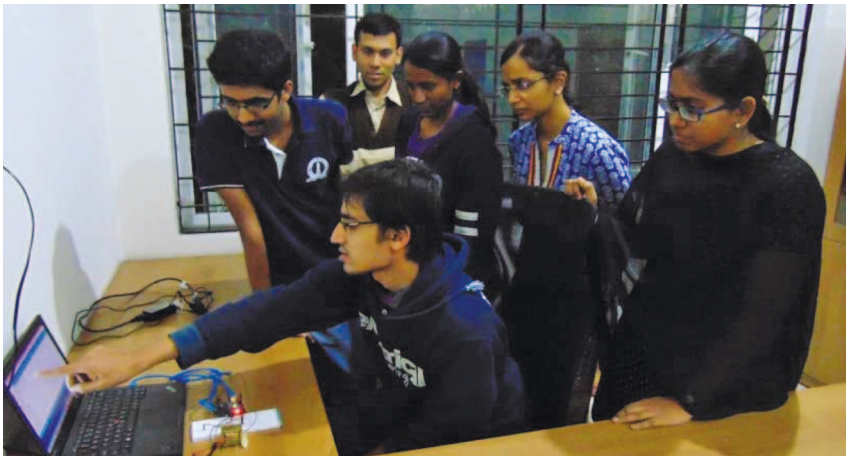

FIGURE 9. Team Vidyut from India won third prize.

Team Vidyut

Team Vidyut (Figure 9) was formed by the collaborated efforts of undergraduate students from the National Institute of Technology–Karnatak, Surathkal (NIT-K) and Indian Institute of Technology—Madras (IIT-M), along with graduate and faculty mentors from the Indian Institute of Science–Bangalore (IISc) where the undergraduate students first met and interned. Returning to their universities in the last month of the competition did not hamper the undergraduate students' teamwork, as they continued to make progress by frequent e-mails and regular phone calls. The team has a perfect gender balance with two female and two male undergraduate students and leveraged the complementary strengths of the members.

- "'Vidyut' means electricity in many Indian languages…Although coordinating amongst ourselves had become a challenge by itself, the sense of team spirit grew in us, as we worked for the competition."—Team Vidyut
- "As an undergraduate, it was very exciting to work on a real-world problem. … Coding was made easier, thanks to MATLAB"—Priyadarshini Savan Roshan, NIT-K
- "In addition to the technical skills gained, this challenge helped me coordinate and communicate better among a team"—Supriya Nagesh, NIT-K
- "Attending the finals in Shanghai was an amazing experience where we had a chance to observe the different views taken by the other teams to approach the same problem. On the whole, participating in the SP Cup proved to be a great learning experience with memorable moments to cherish"—G. Nisha Meenakshi, IISc, graduate mentor.

More reflections from SP Cup finalists and participants along with project reports of selected teams can be found on the IEEE SigPort repository at http://www.sigport.org/events/sp-cup-project-reports. Figure 10 shows a few selected photos provided by the participating teams that showcased their teamwork during the competition.

In closing, we would like to convey our heartfelt congratulations to the winners and teams that received honorable mentions on their excellent performances! Thanks all participants for making IEEE SP Cup 2016 successful! As you read through this issue of *IEEE Signal Processing Magazine*, you will see that the 2017 IEEE SP Cup competition has been announced (see page 5). Please encourage students you know to take part in the competition, mentor a student team if you can, come to support in ways feasible, and stay tuned for another edition of the IEEE SP Cup Global Student Competition!

Acknowledgments

As the SP Cup 2016 organizing committee, we would like to express our

FIGURE 10. Behind-the-scenes teamwork photos of the SP Cup 2016 teams that received special recognitions and honorable mentions (from the top, counter-clockwise) Team UpatrasECE, Greece; Team The Enforcers, Serbia; Team IIT Hyderabad, India; and Team UNStoppable, Serbia.

appreciation to Kenneth Lam, Stefano Tubaro, and Houman Zarrinkoub, who took part in the judging process, and the contributions and assistance from Gwenael Doërr and Chau-Wai Wong. Min Wu and Adi Hajj-Ahmad thank the U.S. National Science Foundation for the research grants ECCS#1309623 and CCF#1320803 that provided a foundation for developing the technical tasks in this SP Cup.

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