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References

[1] F. M. R. Silva and M. Veloso, "Towards table tennis with a quadrotor autonomous learning robot and onboard vision," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)*, 2015, pp. 649–655. doi: 10.1109/IROS.2015.7353441.

[2] D. Silver, T. Hubert, J. Schrittwieser, I. Antonoglou, M. Lai, A. Guez, M. Lanctot, L. Sifre et al., "A general reinforcement learning algorithm that masters chess, shogi, and Go through self-play," *Science*, vol. 362, no. 6419, pp. 1140–1144, 2018. doi: 10.1126/science.aar6404.

[3] T. T. Nguyen, T. Silander, Z. Li, and T.-Y. Leong, "Scalable transfer learning in heterogeneous, dynamic environments," *Artif. Intell.*, vol. 247, pp. 70–94, June 2017. doi: 10.1016/j.artint.2015.09.013.

[4] M. Buehler, K. Iagnemma, and S. Singh, *The DARPA Urban Challenge. Autonomous Vehicles in City Traffic*. Berlin: Springer-Verlag, 2009.

[5] T. Nothdurft, P. Hecker, S. Ohl, F. Saust, M. Maurer, A. Reschka, and J. R. Böhmer, "Stadtpilot: First fully autonomous test drives in urban traffic," in *Proc. 14th Int. IEEE Conf. Intelligent Transportation Systems (ITSC)*, 2011, pp. 919–924. doi: 10.1109/ITSC.2011.6082883.

[6] A. Broggi, P. Cerri, S. Debattisti, M. C. Laghi, P. Medici, M. Panciroli, and A. Prioletti, "PROUD-Public road urban driverless test: Architecture and results," in *Proc. IEEE Intelligent Vehicles Symp.*, 2014, pp. 648–654. doi: 10.1109/IVS.2014.6856478.

[7] M. M. T. S. Sivaraman, "Looking at vehicles on the road: A survey of vision-based vehicle detection, tracking, and behavior analysis," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 4, pp. 1773–1795, 2013. doi: 10.1109/TITS.2013.2266661.

[8] Y. Yusof, H. A. H. Mansor, and A. Ahmad, "Formulation of a lightweight hybrid ai algorithm towards self-learning autonomous systems," in *Proc. IEEE Conf. Systems, Process and Control (ICSPC)*, 2016, pp. 142–147. doi: 10.1109/SPC.2016.7920719.

[9] X. Zhang, X. Ruan, Y. Xiao, and J. Huang, "Sensorimotor self-learning model based on operant conditioning for two-wheeled robot," *J. Shanghai Jiaotong University (Sci.)*, vol. 22, no. 2, pp. 148–155, 2017. doi: 10.1007/s12204-017-1814-8.

[10] R. Bonetto, M. Soldan, A. Lanaro, S. Milani, and M. Rossi, Seq2Seq RNN based gait anomaly detection from smartphone acquired multimodal motion data. 2019. [Online]. Available: arXiv:1911.08608

[11] H. S. Malvar, L.-w. He, and R. Cutler, "High-quality linear interpolation for demosaicing of Bayer-patterned color images," in *Proc. IEEE Int. Conf. Acoustics, Speech, and Signal Processing*, vol. 3, pp. iii–485, May 2004. doi: 10.1109/ICASSP.2004.1326587.

[12] C. Zach, T. Pock, and H. Bischof, "A duality based approach for realtime TV-L 1 optical flow," in *Joint Pattern Recognition Symp.*, 2007, pp. 214–223. doi: 10.1007/978-3-540-74936-3_22.

[13] A. Krizhevsky, I. Sutskever, and G. E. Hinton, "Imagenet classification with deep convolutional neural networks," in *Proc. Advances Neural Information Processing Systems*, 2012, pp. 1097–1105.

[14] K. He, X. Zhang, S. Ren, and J. Sun, "Deep residual learning for image recognition," in *Proc. IEEE Conf. Computer Vision and Pattern Recognition*, 2016, pp. 770–778. doi: 10.1109/CVPR.2016.90.

[15] V. Badrinarayanan, A. Handa, and R. Cipolla, SegNet: A deep convolutional encoder-decoder architecture for robust semantic pixel-wise labelling. 2015. [Online]. Available: arXiv:1505.07293

[16] S. Ahmad, A. Lavin, S. Purdy, and Z. Agha, "Unsupervised real-time anomaly detection for streaming data," *Neurocomputing*, vol. 262, pp. 134–147, Nov. 2017. doi: 10.1016/j.neucom.2017.04.070.

[17] M. Munir, S. A. Siddiqui, A. Dengel, and S. Ahmed, "DeepAnT: A deep learning approach for unsupervised anomaly detection in time series," *IEEE Access*, vol. 7, pp. 1991–2005, Dec. 2018. doi: 10.1109/ACCESS.2018.2886457.

[18] G. Pang, C. Shen, and A. van den Hengel, "Deep anomaly detection with deviation networks," in *Proc. 25th ACM SIGKDD Int. Conf. Knowledge Discovery & Data Mining*, 2019, pp. 353–362. doi: 10.1145/3292500.3330871.

[19] R. Bhatia, *Positive Definite Matrices*, vol. 24. Princeton, NJ: Princeton Univ. Press, 2009.

[20] C. Chen, R. Jafari, and N. Kehtarnavaz, "UTD-MHAD: A multimodal dataset for human action recognition utilizing a depth camera and a wearable inertial sensor," in *Proc. IEEE Int. Conf. Image Processing (ICIP)*, 2015, pp. 168–172. doi: 10.1109/ICIP.2015.7350781.

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Let There Be a Beam

Highlights from the 2020 IEEE 5-Minute Video Clip Contest

The annual IEEE 5-Minute Video Clip Contest (5-MICC) was launched by the IEEE Signal Processing Society (SPS), and beamforming, which has a wide range of applications in radar, sonar, microphone arrays, radio astronomy, seismology, medical diagnosis and treatment, and wireless communications, was chosen as this year's topic. After two stages of fierce competition, three finalist videos were selected by the organizing committee and placed online for public voting. The first one is about fast beam alignment in millimeter-wave (mm-wave) radios, the second

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is about coprime beamforming and its application to speech enhancement, and the third is about an indoor localization system employing a synthetic aperture-based beamforming approach. Taking into consideration the public voting results, the panel of judges decided the final ranking of the three videos. Highlights of the whole event are provided in this article, including a general introduction to beamforming.

The new 5-MICC was presented by the SPS alongside ICASSP in Barcelona, Spain (May 2020). It is an annual event and is open to submissions from IEEE SPS members of various backgrounds, such as high school, undergraduate, and postgraduate students as well as researchers from all over the world. Each participating team must be composed of 1) one faculty member (the supervisor), 2) no more than one graduate student (the tutor), and 3) at least three but no more than five undergraduates. At least three undergraduate team members must either be IEEE SPS members or student members by the time they submit the full 5-min video. The aim of the 5-MICC is to help promote the indispensable role signal processing plays in our everyday lives and encourage more young people to pursue a career in signal processing by creating video clips that "highlight and convey excitement about signal processing in the broad sense—including fundamentals, image, video, audio, speech, communication, radar, language, knowledge, human and machine learning, and other forms of information bearing data and signals."

There are three stages of the contest: the submission of 30-s trailers, the submission of a full 5-min video, and the final contest held at ICASSP each year. The three finalist teams' 5-min videos will be available on the ICASSP website and are voted on by the conference participants. The final ranking will be decided by the judging panel and will also take into account the popular vote. The finalist teams will be invited to the ICASSP Conference Banquet as well as the Student Career Luncheon so that they can meet and talk with SPS leaders and global experts.

The topic

For the inaugural running of this contest, the chosen topic this year was beamforming. Beamforming is one of the major areas of sensor array signal processing research and has been studied extensively in the past due to its wide range of applications in radar, sonar, microphone arrays, radio astronomy, seismology, medical diagnosis and treatment, and wireless communications [1]–[4]. It involves multiple sensors (microphones, antennas, hydrophones, and so on) placed at different spatial locations to process the received/transmitted signals for enhanced signal reception or transmission, while at the same time achieving effective interference reduction.

Traditionally, beamforming is mainly designed for line-of-sight (LoS) transmission and reception, such as radar and many speech-enhancement scenarios using microphone arrays—physically forming a beam in the process—that points to different directions around the sensor array system. However, with the arrival of the age of mobile communications and due to its strong multipath effect, the result of beamforming between the user equipment and the base station will not necessarily form a real beam in space but rather an overall enhanced signal transmission link between them. Today, any signal processing process that achieves the enhancement of the desired signal while reducing the effect of interference can be considered as some form of beamforming. One interesting development is that, with the introduction of massive multiple-input, multiple-output technology and mm-wave communications in 5G [5]–[7], the LoS case is becoming more and more important in wireless communications.

Depending on the array geometry, we can have 1D (linear), 2D (planar), or 3D (volumetric) beamformers.

In general, beamforming can be classified in different ways. Depending on the array geometry, we can have 1D (linear), 2D (planar), or 3D (volumetric) beamformers. Contingent on the format of signal processing, we can have either analog or digital beamforming. With the advancement of digital technology, analog techniques seem to be outdated these days. However, when a large number of sensors are working at high frequencies with a wide bandwidth, the extremely high cost associated with the large number of high-speed analog-to-digital converters and their high-level power consumption will render a completely digital solution practically infeasible, thus making a hybrid beamforming structure preferred in this case. Depending on whether or not the beamforming process is determined by the specific received signals, we can have either a data-independent/fixed beamformer or a data-dependent/adaptive beamformer [1], [3], [8]. A widely used example for the fixed case is the delay-and-sum beamformer, while the Capon beamformer and the Frost beamformer/generalized sidelobe canceler are well known for the adaptive case [3], [4].

Depending on the relative bandwidth of the signals, we can have either a narrow-band or a wideband/broadband beamformer. These two classes of beamformers have different signal models and implementation structures. For the narrow-band case, only one coefficient is attached to each sensor; as a result, for the receiving mode, the beamformer output will be an instantaneous linear combination of the received sensor signals. For the wideband case, either a tapped or sensor delay-line structure is needed for effective beamforming [3]. Whether to adopt the narrow-band or the wideband structure depends on the relative bandwidth of the signals; however, this is not simply a calculation of the ratio between the bandwidth of the signal and its center frequency, and it is also related to the array aperture.

A further insight is to look at the correlation between the signals received at the two opposite ends of the array [9]. If the correlation value is not high, then a simultaneous linear combination of the multiple sensor signals will not help much with enhancing the signal of interest, and a wideband structure can then be employed to improve the performance. One example is adaptive beamforming for distributed unmanned aerial vehicles (UAVs), where each UAV carries a sensor array of its own (a subarray), and together they form a distributed array system. Although the signal is narrowband for each subarray, due to its distributed nature, the signals received by different subarrays are not correlated with each other any more; as a result, a wideband beamforming structure has to be employed for effective beamforming [10]. Another wideband beamforming example is speech enhancement using microphone arrays, which has become even more important in the era of artificial intelligence.

The contest

The title of the specific call for this year's 5-MICC was "Let There Be a Beam." Submitted videos could cover any aspects of beamforming-related areas. For example, it could be a general introduction to beamforming and how it works, one or more specific beamforming techniques, recent developments in beamforming and future directions, one or more specific applications of beamforming, various demonstrations of beamforming devices and systems, and so on. To engage the broad signal processing community to come up with creative ideas, "open topic" video submissions were also accepted, even if they were not related to beamforming.

The organizing committee consisted of four members, including Dr. Wei Liu (the University of Sheffield, United Kingdom), Dr. Mohammad Reza Anbiyaei (Alzahra University, Iran), Dr. Xue Jiang (Shanghai Jiao Tong University, China), and Dr. Lei Zhang (the University of Glasgow, United Kingdom). The contest received submissions from Australia, China, India, and the United States, and after two stages of fierce competition, three finalists were left: two from the United States and one from Australia. Their three videos were placed online for public voting. Due to the outbreak of the COVID-19 virus, ICASSP 2020 was transformed into a fully virtual conference. Accordingly, it was decided that the voting would be open not just to ICASSP participants but also to the general public. To reduce the possibility of voting system abuse, information about the name, affiliation, and email address of each voter was required for the vote to be valid. The voting system was open from 22 April to 6 May 2020, bringing in a total of approximately 5,500 votes.

The judging panel was composed of seven members, which included the four organizing committee members, along with Dr. Lucio Marcenaro (the University of Genova, Italy), Prof. K.V.S. Hari (the Indian Institute of Science, Bangalore), and Prof. Nikolaos Sidiropoulos (the University of Virginia, United States). Also taking into consideration the public voting results, the panel decided on the final ranking of the three finalist teams as follows. The grand prize of US$5,000 was awarded to a team from the University of California, Irvine, while the two runner-up prizes, with equal awards of US$2,500 (i.e., two equal second-place positions), were awarded to a team from the University of Texas at Austin and the University of Wollongong, Australia, respectively. The videos are available on the IEEE SPS YouTube channel (https://www.youtube.com/playlist?list=PLcZOnmyqlalaq96E2GyjWZKhdgjAXWp9x) or on the IEEE SPS website (https://signalprocessingsociety.org/get-involved/five-minute-video-clip-contest).

Whether to adopt the narrow-band or the wideband structure depends on the relative bandwidth of the signals.

Grand prize

The grand prize for the 5-MICC was awarded for "An Indoor Localization System Exploiting LTE Signals: A Synthetic Aperture-Based Beamforming Approach to Mitigate Multipath":

- *Affiliation*: the University of California, Irvine
- *Undergraduate students*: Zainab Ashai, Xinyi Zhong, and Qitai Meng
- *Tutor*: Ali A. Abdallah
- *Supervisor*: Prof. Zaher M. Kassas
- *Description*: This video presented an approach for indoor localization using long-term evolution (LTE) carrier-phase measurements. To mitigate the non-LoS (NLoS) multipath effect for the localization of time-of-arrival estimation-based algorithms [11], a so-called synthetic aperture navigation (SAN) beamforming approach was presented [12]. The four steps of SAN are 1) estimate all of the LoS and NLoS paths in the received signals, 2) select the LoS from among all of the identified paths, 3) beamform toward the direction of the LoS while minimizing the NLoS effect, and 4) process the received LoS signal and estimate the parameters of interest with the aid of an extended Kalman filter. The video used animations vividly showing the principle of synthetic aperture beamforming [Figure 1(a)]. Even more impressively, an experimental validation was carried out with step-by-step technical and visual presentations through four subvideos, as shown in a snapshot in Figure 1(b). A National Instrument universal software radio peripheral 2955 equipped with four consumer-grade cellular omnidirectional Laird antennas was used as the receiver mounted on a cart (top right) to listen to six LTE eNodeBs from three U.S. cellular providers. The signals were then sampled and transferred to a laptop computer for postprocessing, where the real-time direction-of-arrival (DOA) estimation results were shown in the left part of Figure 1(b). At the bottom right, the ground truth was provided, and overall, the proposed LTE-SAN framework outperformed the LTE standalone solution with a position root mean square error of 3.93 versus 7.19 m.

Runners up

One of two runner-up prizes at 5-MICC was awarded for "Fast Beam Alignment in Millimeter Wave Radios":

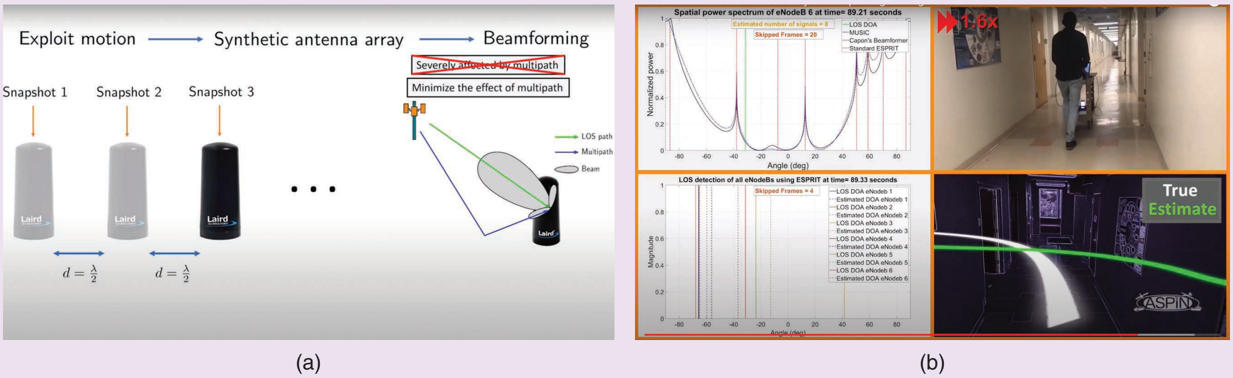

FIGURE 1. The video for indoor localization exploiting LTE signals. (a) A synthetic aperture-based array for beamforming and (b) the experimental validation process for SAN.

- *Affiliation*: the University of Texas at Austin
- *Undergraduate Students*: Juliet M. Leger, Frida K. Maldonado, and Kayla N. Tran
- *Tutor*: Nitin J. Myers
- *Supervisor*: Prof. Robert W. Heath Jr.
- *Description*: The video explained the concept of beamforming of mm-wave radios used in 5G and IEEE 802.11ad/ay devices and pointed out that the conventional exhaustive search over the 2D discrete Fourier transform codebook would result in a substantial training overhead [7]. To implement fast beam alignment in mm-wave radios [Figure 2(a)], the team proposed the compressive-beam-alignment method by utilizing the sparsity of the beamspace matrix. In this way, the best beam can be estimated using random antenna switchings with much lower overhead than that of the exhaustive search. One-bit phased arrays are promising in terms of the hardware complexity, cost, and power consumption for large-scale systems [13]. Therefore, by noticing that the antenna switching is equivalent to the 2D-circulant sensing of a Dirac matrix, the team addressed the fast beam-alignment issue with low-resolution phase shifters, i.e., random 2D-circulant sensing using a perfect binary array [Figure 2(b)] [14]. The team utilized 100 LoS channels from the New York University simulator [15] to evaluate the effectiveness of the proposed algorithms. It was demonstrated that the overhead of the proposed random antenna switching and circulant sensing is only 7 and 3% of that of an exhaustive search, respectively.

To implement fast beam alignment in mm-wave radios, the team proposed the compressive-beam-alignment method by utilizing the sparsity of the beamspace matrix.

A second runner-up prize was awarded for "Co-Prime Beamforming and Its Applications to Speech Processing":

- *Affiliation*: the University of Wollongong, Australia
- *Undergraduate students*: Hualin Ren, Zishan Gao, and Hantao Zeng
- *Tutor*: Jiahong Zhao
- *Supervisor*: Prof. Christian Ritz
- *Description*: This video introduced a new concept called *coprime beamforming* and its applications to speech processing [Figure 3(a)] in a coherent and easy-to-understand way. The coprime array (CPA) was proposed in 2010 [16] [Figure 3(b)] and has been a very active field of research in recent years. Two structures of the CPAs were reviewed in this video, namely, coprime circular microphone arrays (CPCMAs) and semicoprime MAs (SCPMAs). The CPCMA is formed by interleaving two uniform, circular subarrays with a shared reference microphone [17], while the SCPMA is the product of interleaving three uniform subarrays [18]. The signals received from subarrays are aggregated using a processor to generate the output of the whole beamformer. One advantage of the SCPMA is that it has lower side lobes than does the CPCMA. In addition to beamforming, the DOA application of CPAs using a conventional steered-response power-phase transform (SRP-PHAT) was also described in the video. For the SRP-PHAT method, the angle corresponding to the peak SRP value was calculated and used to estimate the DOA of the source signal. This estimation was then further improved using a histogram-based stochastic algorithm.

Summary

As a new event launched by our SPS, the 5-MICC has proved to be a success both in terms of public engagement and the quality of submissions, as seen from the large number of public votes cast for the three finalist videos. The only regret is that the participants, and especially the finalist teams, the organizing committee, and the judging panel members could not meet in person at ICASSP 2020 due to the COVID-19 pandemic. Moreover, there were some delays at different stages of the contest, which could be avoided with a better plan and a clearer

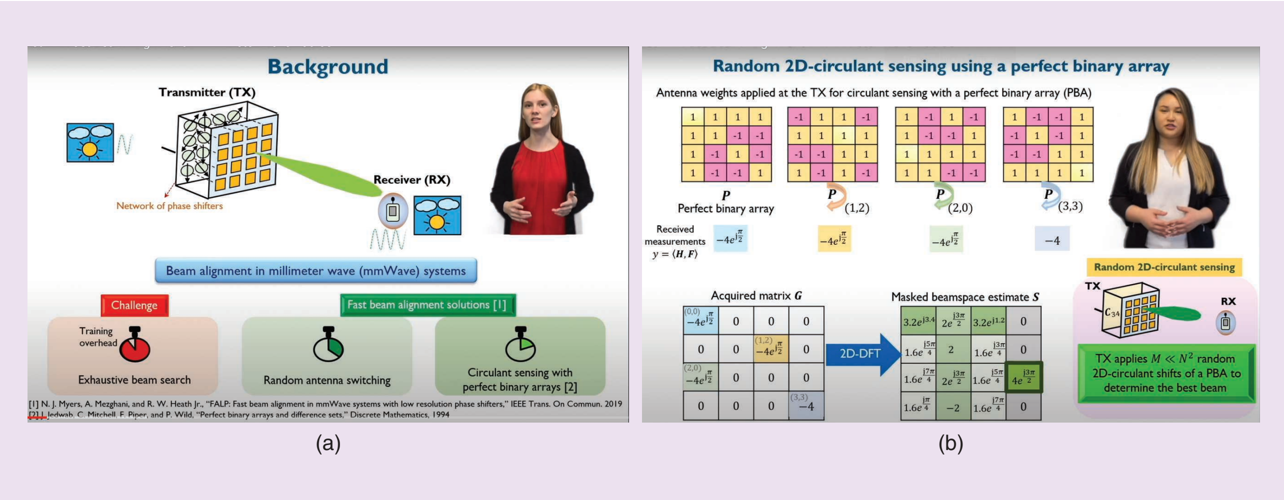

FIGURE 2. The video for fast beam alignment in mm-wave radios. (a) The background of the beam-alignment problem and (b) the random 2D-circulant sensing using a perfect binary array (PBA). Tx: transmitter; Rx: receiver; DFT: discrete Fourier transform.

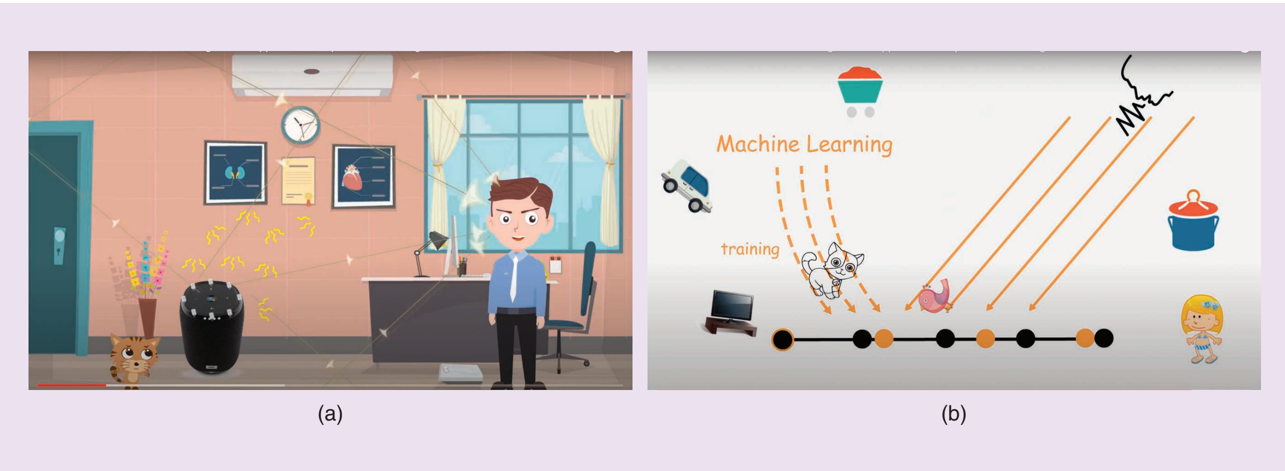

FIGURE 3. The video for coprime array beamforming and its applications. (a) A speech processing context and (b) the coprime array concept and application.

understanding of the time required for preparing for the submission/voting platform and for processing the submissions. Inspired by the achievements of the 2020 5-MICC, we very much look forward to even more successful contests next year (the SPS has decided that there will be two 5-MICC contests in 2021, one with ICASSP and one with ICIP).

Acknowledgments

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References

[1] H. L. Van Trees, *Optimum Array Processing: Part IV of Detection, Estimation, and Modulation Theory*. Hoboken, NJ: Wiley, 2002.

[2] J. Benesty, J. D. Chen, and Y. T. Huang, *Microphone Array Signal Processing*. Berlin: Springer-Verlag, 2008.

[3] W. Liu and S. Weiss, *Wideband Beamforming: Concepts and Techniques*. Chichester, U.K.: Wiley, 2010.

[4] Q. Luo, S. Gao, W. Liu, and C. Gu, *Low-Cost Smart Antennas*. Hoboken, NJ: Wiley, Mar. 2019.

[5] F. Boccardi, R. W. Heath, A. Lozano, T. L. Marzetta, and P. Popovski, “Five disruptive technology directions for 5G,” *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 74–80, Feb. 2014. doi: 10.1109/MCOM.2014.6736746.

[6] T. L. Marzetta, E. G. Larsson, H. Yang, and H. Q. Ngo, *Fundamentals of Massive MIMO*. Cambridge, U.K.: Cambridge Univ. Press, 2016.

[7] R. W. Heath Jr., N. Gonzalez-Prelcic, S. Rangan, W. Roh, and A. M. Sayeed, “An overview of signal processing techniques for millimeter wave MIMO systems,” *IEEE J. Sel. Topics Signal Process.*, vol. 10, no. 3, pp. 436–453, 2016. doi: 10.1109/JSTSP.2016.2523924.

[8] B. D. Van Veen and K. M. Buckley, “Beamforming: A versatile approach to spatial filtering,” *IEEE Acoust., Speech, Signal Process. Mag.*, vol. 5, no. 2, pp. 4–24, Apr. 1988. doi: 10.1109/53.665.

[9] R. T. Compton, *Adaptive Antennas: Concepts and Performance*. Englewood Cliffs, NJ: Prentice Hall, 1988.

[10] Q. Shen, W. Liu, L. Wang, and Y. Liu, “Adaptive beamforming for target detection and surveillance based on distributed unmanned aerial vehicle platforms,” *IEEE Access*, vol. 6, pp. 60,812–60,823, Oct. 2018. doi: 10.1109/ACCESS.2018.2875560.

[11] A. A. Abdallah, K. Shamaei, and Z. M. Kassas, “Performance characterization of an indoor localization system with LTE code and carrier phase measurements and an IMU,” in *Proc. Int. Conf. Indoor Positioning and Indoor Navigation (IPIN)*, 2019, pp. 1–8. doi: 10.1109/IPIN.2019.8911791.

[12] A. A. Abdallah and Z. M. Kassas, “Evaluation of feedback and feedforward coupling of synthetic aperture navigation with LTE signals,” in *Proc. IEEE 90th Vehicular Technology Conf. (VTC2019-Fall)*, 2019, pp. 1–6. doi: 10.1109/VTCFall.2019.8891521.

[13] N. J. Myers, A. Mezghani, and R. W. Heath, “FALP: Fast beam alignment in mmWave systems with low-resolution phase shifters,” *IEEE Trans. Commun.*, vol. 67, no. 12, pp. 8739–8753, Dec. 2019. doi: 10.1109/TCOMM.2019.2941490.

[14] J. Jedwab, C. Mitchell, F. Piper, and P. Wild, “Perfect binary arrays and difference sets,” *Discrete Math.*, vol. 125, no. 1–3, pp. 241–254, 1994. doi: 10.1016/0012-365X(94)90165-1.

[15] S. Sun, G. R. MacCartney, and T. S. Rappaport, “A novel millimeter-wave channel simulator and applications for 5G wireless communications,” in *Proc. IEEE Int. Conf. Communications (ICC)*, Paris, France, May 2017. doi: 10.1109/ICC.2017.7996792.

[16] P. P. Vaidyanathan and P. Pal, “Sparse sensing with co-prime samplers and arrays,” *IEEE Trans. Signal Process.*, vol. 59, no. 2, pp. 573–586, Feb. 2011. doi: 10.1109/TSP.2010.2089682.

[17] J. Zhao and C. Ritz, “Co-prime circular microphone arrays and their application to direction of arrival estimation of speech sources,” in *Proc. IEEE Int. Conf. Acoustics, Speech and Signal Processing (ICASSP)*, 2019, pp. 800–804. doi: 10.1109/ICASSP.2019.8682876.

[18] J. Zhao and C. Ritz, “Semi-coprime microphone arrays for estimating direction of arrival of speech sources,” in *Proc. Asia-Pacific Signal and Information Processing Association Annu. Summit and Conf. (APSIPA ASC)*, 2019, pp. 308–313. doi: 10.1109/APSIPAASC47483.2019.9023143.

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