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Waveform-Agile Sensing and Processing

Imagine being able to recognize objects under water while swimming, just like dolphins do, or being able to locate objects while actively homing in, just like bats do. Echolocation in these mammals has evolved over millions of years. Initial returns are processed to locate and identify objects, and then the mammal adapts the time-frequency signature of the emitting waveform to the environment and hunting mechanism. Instances of waveform adaptive sensing in nature have the potential to provide insight into man-made applications such as radar and sonar. News headlines, such as "Sensors for Bat-Inspired Spy Plane Under Development ..." ("Research News," *Michigan Today*, University of Michigan, March 2008) may be portents for the value of waveform agility.

The narrowband ambiguity function, introduced by P.M. Woodward in his 1953 text, provides a mathematical framework for reasoning about active sensing. Essentially it describes the effect of range and Doppler on the matched filter receiver response. Woodward captures the state of knowledge in 1953 as follows: "… the basic question of what to transmit remains substantially unanswered." He may have failed to do adequate justice to his own contributions, but certainly many advances have been made since 1953, and many of these are enabled by the mathematical framework afforded by the ambiguity function.

In the last decade, the emergence of prototype radar systems equipped with highly agile, software-driven waveform generators has provided the ability to change the transmit waveform at each time step to match environments and sensing objectives. In fact, the focus of our special issue is the development of signal processing techniques that are able to take full advantage of advances in radar systems. Phased array radars and space-time adaptive processing illuminate the value of waveform diversity with respect to time, space, frequency, and polarization. Articles in this special issue exploit spatial diversity on transmit and receive, use polarization diversity to resolve close targets and separate targets from clutter, and employ waveform diversity to increase sensing performance. Since there is an infinity of possible waveforms, it becomes critical to manage complexity by developing waveform libraries and optimization methods. The optimization is needed to select the transmit waveform at each time step to reduce estimation errors, increase collected information, or schedule sensors. Articles in this special issue show that adaptation of waveforms with highly localized correlation properties or time-frequency characteristics that match echo-locating signatures can improve sensing performance and reduce sensor usage leading to greater system efficiency.

The special issue begins by considering the fundamentals of waveforms and waveform libraries; it then describes the resources represented by waveform agility, design, and diversity and the available approaches to adaptive detection, estimation, and tracking; it ends with lessons learned from the bio-sonar of bats. In fact, the articles were selected in part to tell a story, and in our selection process, we avoided overlaps between articles or digressing from the story. The editors would like to acknowledge the insights they have obtained from their participation in two Department of Defense (DoD) research programs: a current multidisciplinary university research initiative (MURI) on adaptive waveform design for full spectral dominance, directed by the Air Force Office of Scientific Research (AFOSR), and the Defense Advanced Research Projects Agency (DARPA) program on waveform-agile sensing (WAS). These programs are in collaboration with the Air Force Research Laboratory (AFRL) and the Naval Research Laboratory (NRL). We now briefly preview the six articles in this special issue.

The importance of waveform libraries and information measures in waveform-agile sensing is discussed by Cochran, Suvorova, Howard, and Moran, in their article "Waveform Libraries." In the context of radar scheduling, the authors exploit transmitter agility by selecting the radar signal according to operational criteria. They also present closed-loop waveform scheduling for radar, and the design of small but effective waveform libraries, using information theoretic measures to assess their utility. Good libraries are designed offline, thereby replacing the real-time challenge of waveform design with the simpler task of selecting waveforms from a library.

The role of the ambiguity function (AF) in radar and its relevance to waveform agility is reviewed by Benedetto, Konstantinidis, and Rangaswamy, in their article "Phase-Coded Waveforms and Their Design." They consider constant amplitude zero autocorrelation (CAZAC) sequences that are important in waveform design due to their optimal transmission efficiency and tight time localization properties. Discrete periodic and aperiodic AFs are used to compare different CAZACs, and the AF behavior of phase-coded waveforms is analyzed. The processing techniques

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discussed are from classical signal processing theory and also employ number and frame theoretic ideas, which naturally arise in this framework.

Sixty years ago, efforts by Golay to improve the sensitivity of far infrared spectrometry led to the discovery of pairs of complementary sequences. Shortly thereafter, Welti proposed to use Golay sequences in radar, but they have found very limited application to date. In "Waveform Diversity in Radar Signal Processing," Calderbank, Howard, and Moran demonstrate that suitably transmitted and processed radar waveforms based on Golay sequences provide new primitives for adaptive waveform transmission. The adaptive transmission enables improved detection and finer resolution, while managing computational complexity at the receiver.

Polarization diversity provides meaningful information to discriminate targets from clutter. Hurtado, Xiao, and Nehorai review the concept of polarimetric diversity and discuss methods for the optimal adaptive design of radar polarization in their article, "Target Estimation, Detection, and Tracking." A closed-loop system is considered that sequentially estimates the target and clutter scattering parameters and then uses the estimates to optimally select the polarization of subsequent waveforms. This adaptive system is shown to significantly improve radar capabilities when compared with fixed-polarization schemes, as it can achieve optimal performance in several operating modes, including detection, estimation, and tracking.

The choice of agile waveform in sensing can be affected by many factors, including whether the sensing environment is narrowband or wideband, is immersed in heavy clutter or strong noise. In their article, "Waveform-Agile Sensing for Tracking," Sira, Li, Papandreou-Suppappola, Morrell, Cochran, and Rangaswamy discuss how tracking can exploit the optimization of waveform-dependent cost or objective functions, such as tracking errors and information retrieval, to update the transmitted waveform for the next time step. Waveforms with nonlinear time-frequency signatures have been found to be more conducive to adverse environmental conditions and these waveforms are shown to better match the bio-sonar mechanism of mammals.

The first five articles provide overviews on waveform agility in sensing. Vespe, Jones, and Baker, in their article "Lessons for Radar," provide an overview on the echolocating world of mammals and how it relates to waveform agility. They show that bats employ various strategies for survival or communication that could provide critical insight into autonomous navigation, collision avoidance, and automatic target classification. After a discussion on how bats vary their emitted waveforms, the bat echolocation behavior is related to exploiting waveform diversity in radar. The authors also investigate how bats perform autonomous orientation and relate it to potentially more reliable and robust autonomous systems.

We hope you find the reading as exciting for you as the research is for us! To view a more extensive reference list, visit the WASPer (waveform-agile sensing and processing e-resources) Web site at http://www.fulton.asu.edu/~apapand/WASPer. We conclude by thanking the reviewers, authors, and Prof. Williams (special issue area editor) for their guidance. In the future, we look to see the research presented here realize the promise of bat-like agility in man-made systems for active sensing. [SP]

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Under the leadership of former Editor-in-Chief, Prof. Shih-Fu Chang, and through the diligent work of his editorial team as well as the foundational work of our society's Vice-President for Publications, Prof. Ray Liu, *SPM* is in excellent condition as testified by its top ranking among over 200 electrical engineering publications worldwide. During the transition period, I received Prof. Chang's and Prof. Liu's invaluable guidance and support, for which I am wholeheartedly grateful. I am also fortunate to have Profs. Antonio Ortega, Dan Schonfeld, Ghassan AlRegib, and Min Wu, who agreed to shoulder the responsibility of area editors for feature articles, special issues, columns/forums, and e-newsletter, respectively. They will work closely with me and the editorial board to fulfill the expectations of you, our readers.

Different from other publications that focus on new research results, the magazine includes tutorial articles with comprehensive surveys of important theories, algorithms, tools, and applications related to signal processing. *SPM* is received bimonthly by every member of the IEEE Signal Processing Society. Each issue includes articles from three main categories—special issue articles, feature articles, and columns/forums articles. The recently introduced *Inside Signal Processing E-Newsletter* is a monthly electronic publication of *SPM* serving all Society members.

It is not easy to meet the grand challenges in the new golden age of signal processing. We seek your active involvement and participation in shaping *SPM* to one reflecting our whole community's interests, both long term and short term. Contact me for any ideas you may have for improving any section in *SPM*. I welcome you to be an *SPM* author, columnist, guest editor, and/or a reviewer, and to share the optimistic spirit of the community in anticipating the new, exciting era of signal and information processing. [SP]