Maria S. Greco, Jian Li, Teng Long,
and Abdelhak Zoubir

Advances in Radar Systems for Modern Civilian and Commercial Applications: Part 1

Radar was developed during World War II for defense and security applications, and it was initially used for detecting aircrafts and missiles, replacing short range and narrow field-of-view acoustic devices. Since then, radar use has been progressively widened to numerous civilian applications, including airport and harbor traffic control, remote sensing of Earth, wave forecasting and marine climatology, high-precision detection of small surface movements, biomass and deforestation measuring, and volcano and earthquake monitoring. More recently, it has included car cruise control and collision avoidance, monitoring of heartbeats and respiratory function, physiological liquid detection, and monitoring of artery walls and vocal cord movements, with devices that, thanks to the progress of the technology, can in some cases be even smaller than a modern smartphone. Today, the use of radar-like sensors is getting more and more pervasive, and the future will likely see radar as a ubiquitous sensor, devoted to applications completely unexpected when it was used for the first time.

Radar systems can be spaceborne, airborne, or ground based and can be mounted on fixed or moving platforms. They can work in the entire frequency spectrum of megahertz to gigahertz, and even terahertz radars are currently being studied. Their dimensions (antenna included) can go from tens of centimeters to tens of meters, with an emitted power from a few watts to tens of megawatts and a cost from a few hundred to millions of dollars. They are generally used as outdoor sensors, but the safety, reliability, portability, and affordability of small radar devices have made them prime candidates for also being used as indoor sensors inside office buildings, homes, and schools.

In this last scenario, radar possesses unique advantages that complement other sensors, e.g., those that are visual, infrared, or wearable. It is a noncontact device that is insensitive to lighting conditions and is capable of penetrating opaque objects, such as tables or walls, protecting the privacy of the individuals being monitored. In essence, radar backscattering signals can reveal human motion independent of clothing, making it ideal for sensitive environments, such as hospitals, assisted living facilities, restrooms, and bedrooms, where people would not be comfortable placing video cameras.

Whatever the application and the platform, radar systems have the advantage of being used in all weather and light conditions, meaning they can function without interruption or large losses in the quality of service all day and throughout the year. Depending on the application, size, cost, and expected performance, these systems require sophisticated signal processing techniques to extract the necessary information from the observed data that are corrupted by the various kinds of disturbances embedding the useful signal.

This special issue is divided into two parts [part 2 will appear in the September issue of *IEEE Signal Processing Magazine* (*SPM*)]. The goal of both parts of the special issue is to show, in the typically rigorous but easy-to-understand style of the magazine, the main techniques applied in different scenarios by different systems, focusing particularly on some of the new civil and commercial applications. There are, however, no articles dedicated specifically to defense, harbor, or air-traffic control nor on long-range remote sensing. This is not because they are not considered equally important or because they are declining in terms of scientific and market interest, but it is only because they are considered more classic topics that are supposedly more well known by a larger audience.

Part 1 of this special issue opens with an article on indoor applications titled "Radar-Based Human-Motion Recognition With Deep Learning," by Gurbuz and Amin. This first article focuses on radar for indoor monitoring to classify daily human activities, including falls and detection of gait abnormalities. In particular, it discusses recently proposed enhancements of deep-learning classification performance in radar image analysis. The second article, "Radar Signal Processing for Sensing in Assisted Living," by Le Kernec et al., is on a related topic. It considers again an indoor application for vital sign detection

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and activity recognition in assisted living facilities.

Anghel et al.'s article, "Compact Ground-Based Interferometric Synthetic Aperture Radar," focuses on a completely different application: the monitoring of infrastructures through ground-based or spaceborne synthetic aperture radars, a valid alternative to regular in situ topographic surveys, particularly for old structures without any incorporated deformation sensors. The main monostatic and bistatic signal processing techniques for this new application are summarized and discussed with some examples.

The next three articles are dedicated to ground-penetrating radars (GPRs). GPRs have the ability to inspect optically opaque media and provide information on hidden and buried objects (up to depths of some meters). The first two articles of this group, "Applying Ground-Penetrating Radar and Microwave Tomography Data Processing in Cultural Heritage," by Catapano et al., and "The Tomographic Approach to Ground-Penetrating Radar for Underground Exploration and Monitoring," by Ambrosanio et al., focus on multiple tomographic approaches and describe some strategies devoted to reducing artifacts and providing effective 3D images of the scenario being tested for archeological applications and underground monitoring. The third article, by Sun et al., "Advanced Signal Processing Methods for Ground-Penetrating Radar," conversely, is dedicated to the description of different signal processing techniques applied to improve the GPR time resolution and to better estimate the parameters, such as thickness, permittivity, and interface roughness, of the surveyed media in civil engineering.

In "Weather Radar Data Processing and Atmospheric Applications," Falconi and Marzano provide an overview of ground-based, airborne, and spaceborne weather radar systems and related signal processing techniques for retrieving useful geophysical parameters from rain, snow, and volcanic ash clouds. Signal processing of single-polarization is introduced and is then extended to deal with more advanced schemes, such as dual-polarization and multiple-frequency radars.

The last article of part 1 of this special issue is "Principles of Biological Echolocation Applied to Radar Sensing" by Schouten and Steckel. The authors look at radar from a nonclassical perspective, trying to mimic the relevant morphology and signal processing techniques of a bat for improving 3D localization of objects. Radar, coupled with a custom control architecture, is then used as the only source of exteroceptive information during autonomous navigation of a robotic platform.

Acknowledgments

We thank all of the contributors for their outstanding articles that addressed relevant aspect and applications of modern radar systems. We are grateful to *SPM* Editor-in-Chief Robert Heath and IEEE Signal Processing Society Publications Administrator Rebecca Wollman for their continual support and assistance. We very much enjoyed putting together this two-part special issue, and we believe that our readers will enjoy it twice as much.

Guest Editors

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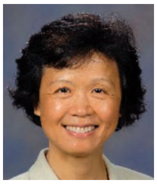

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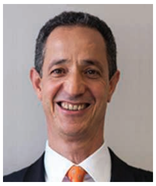

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READER'S CHOICE *(continued from page 9)*

convex optimization is proposed to maximize energy efficiency.

2017

An Application-Specific Protocol Architecture for Wireless Microsensor Networks

Heinzelman, W.B.; Chandrakasan, A.P.; Balakrishnan, H.

Low-energy adaptive clustering hierarchy (LEACH), an application-specific protocol architecture for microsensor networks, is proposed to achieve easy deployment, long system lifetime, low latency, and good application-perceived quality. It includes a new distributed cluster formation technique to enable nodes' self-organization, cluster adaptation and cluster head rotation algorithms to distribute the energy load evenly among nodes, and distributed signal processing techniques to save communication resources. Simulation results show that LEACH can significantly extend system lifetime when compared with general-purpose multihop approaches.

2012

Unmanned Aerial Vehicle With Underlaid Device-to-Device Communications: Performance and Tradeoffs

Mozaffari, M.; Saad, W.; Bennis, M.; Debbah, M.

This paper analyzes the coverage and rate performance of UAV-based wireless communication in the presence of underlaid D2D communication links. It is shown that a maximum system sum rate can be achieved if the UAV altitude is adjusted appropriately based on the D2D user density. In the mobile UAV scenario, it is shown that, to enhance the coverage area, the UAV should stop in more locations over the target area, which in turn leads to an increased delay for downlink users and higher outage probability for D2D users. The tradeoff between coverage and delay required to cover the entire target area is analyzed.

2016

Coverage and Rate Analysis for Millimeter-Wave Cellular Networks

Bai, T.; Heath, R.W.

A stochastic geometry framework to evaluate the coverage and rate performance of millimeter-wave cellular networks is proposed. Using a distance-dependent line-of-sight (LOS) probability function, the locations of the LOS and non-LOS base stations are modeled as two independent nonhomogeneous Poisson point processes. Expressions of the signal-to-interference-plus-noise ratio and the rate coverage probability are derived. Dense networks are analyzed by approximating the LOS region of a user as a fixed LOS ball. It is shown that dense millimeter-wave networks can achieve comparable coverage and much higher data rates than conventional ultrahigh-frequency cellular systems.

2015

Cell-Free Massive MIMO Versus Small Cells

Ngo, H.Q.; Ashikhmin, A.; Yang, H.; Larsson, E.G.; Marzetta, T.L.

This paper analyzes the performance of a cell-free massive MIMO system, where a large number of access points serves a much smaller number of autonomous users over the same time/frequency resources. Closed-form uplink and downlink capacity bounds are derived, considering imperfect channel state information, nonorthogonality of pilot sequences, and power control. Greedy pilot assignment and max-min fairness power control algorithms are proposed. It is shown that cell-free MIMO systems significantly outperform small-cell systems in terms of throughput and immunity to shadow-fading spatial correlation.

2017

The Application of MIMO to Nonorthogonal Multiple Access

Ding, Z.; Adachi, F.; Poor, H.V.

This paper studies the application of MIMO to nonorthogonal multiple access (NOMA) downlink communication systems. A new precoding and detection matrix design for MIMO–NOMA is proposed, and it is shown that MIMO–NOMA can achieve better outage probability than conventional MIMO–OMA. To further increase the performance gap, user pairing is applied to MIMO–NOMA, and both the exact expression for the average sum-rate gap and its high signal-to-noise ratio approximation are derived. The cognitive radio-inspired choices for power allocation coefficients are also proposed to meet various quality-of-service requirements.

2016

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