Microwaves&RF

By KAUE MORCELLES, Independent Technical Writer,
Per Vices Corp., pervices.com

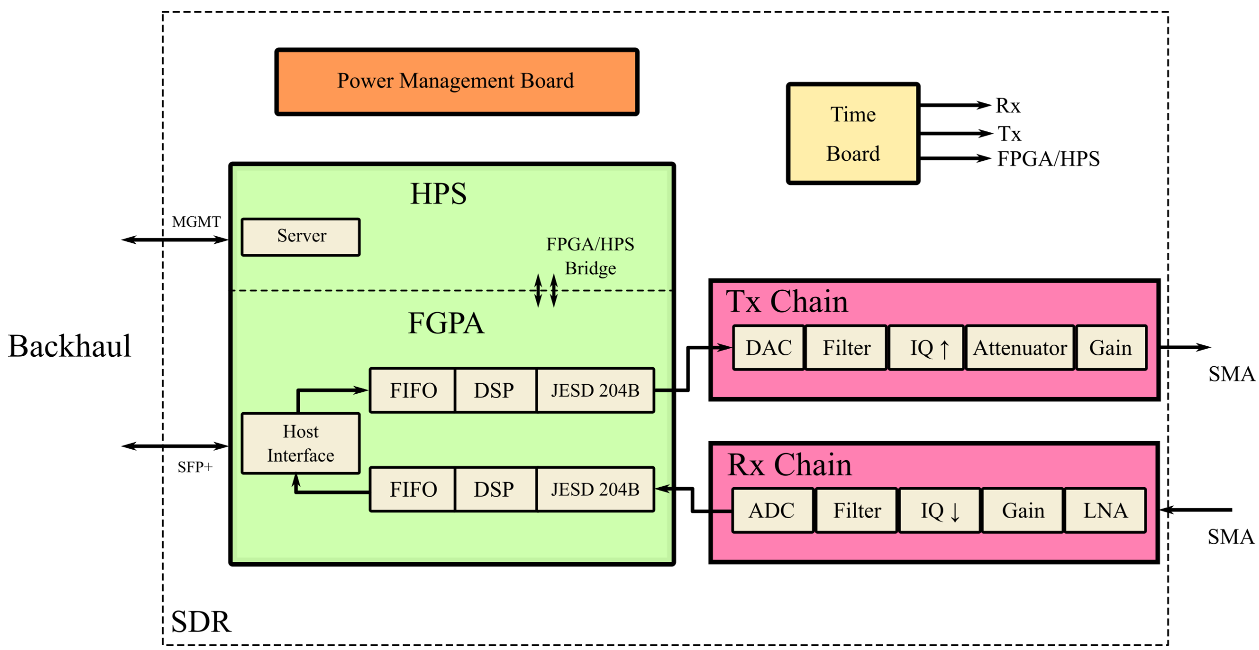
How Software-Defined Radio is Advancing Radar Systems

Radar systems are increasingly important in many industries. However, as they carry out complex techniques, they need transceivers that can meet their needs. Software-defined radio provides a versatile and effective solution.

Radar (or radio detection and ranging) systems are precise and versatile RF instruments that have become indispensable for many industries, playing a significant role in shaping the modern world. From military operations to air traffic control, these systems are now the main tools for monitoring and tracking objects in motion. Naturally, development of novel radar techniques and devices requires significant resources.

However, complex techniques involving multiple channels and anti-jamming waveforms can't be easily performed using traditional RF transceivers. They lack the flexibility and programmability to address dynamic tasks and adapt to different scenarios.

Software-defined radios (SDRs), on the other hand, are digital-based radio transceivers with high levels of versatility, scalability, and adaptability. Thus, they're able to address the changing needs of the industry while also allowing for the implementation of extremely complex and powerful measurement schemes—e.g., beamforming and frequency hopping—that require very low-latency computation of



1. A generic SDR architecture comprises two main parts: the radio front end (RFE, in pink) and the digital back end (green).

multiple RF channels.

In this article, we'll delve into the role of SDR technology in advancing radar systems, enabling these transceivers to adapt to new challenges as well as increasing their overall precision, effectiveness, and size, weight, and power (SWaP) characteristics. Also discussed are the key features and performance benefits that SDRs introduce in the radar industry, as well as some of the challenges that must be overcome in this type of design.

In addition, we'll examine some of the most promising applications of SDR-based radars in industries ranging from aerospace and defense to transportation. The article wraps up with a look at the future of this industry and how it will continue to evolve in response to changing technological and environmental factors.

Basic Concepts of SDRs

Before diving into the implementations of SDR-based radars, we should understand the basic concepts of both devices and how the RF features of SDRs intersect with radar requirements. As the name suggests, software-defined radios are wireless transceivers that implement most of the radio functions in the software domain. They use only the essential analog hardware required to operate the RF chain and pre-process signals.

Thus, the radio's processing functions can be reprogrammed and adjusted without the need for hardware modification. Thus, a single unit essentially can be completely repurposed for a different function without component replacement or physical knob tweaking.

A generic SDR architecture comprises two main parts: the radio front end (RFE) and the digital back end *(Fig. 1)*. The RFE includes receiver (Rx) and transmitter (Tx) functions that operate over a wide tuning range, typically from dc to 18 GHz. Instantaneous bandwidth also is very important in terms of defining the slice of spectrum that can be analyzed at once—the highest-bandwidth SDRs in the market can reach up to 3 GHz per channel.

The digital back end of SDRs contains a field-programmable gate array (FPGA) with on-board DSP for modulation/demodulation, up/downconverting, data packetization, filtering, waveform storage, and to meet custom interface requirements. The FPGA-based architecture enables the SDR to be completely reconfigured and upgraded to support the latest radio protocols and DSP algorithms, which significantly extends the service life of radio equipment.

SDRs also contain multiple independent RF channels with dedicated analog-to-digital and digital-to-analog converters (ADCs/DACs). Multichannel operation combines with the parallel computing capabilities of the FPGA to enable simultaneous transmission and reception of multiple signals with very low latency while still maintaining phase coherency and stability.

Naturally, parallel operation produces a huge amount of data that needs to be sent to/from the host system. Thus, high-end SDRs provide high-speed backhauls based on qSFP+ optical links, which reliably connects the SDR management and data lines with the host system. The main advantage of SDR over conventional architectures is its flexibility and upgradability. It allows for updates and improvements to be made via software updates rather than requiring costly hardware upgrades.

Introduction to Radars

The word "radar" is an acronym for radio detection and ranging, which covers any device capable of detecting a target and evaluating its position and velocity using RF waves. Radar technology plays a crucial role in a variety of industries, including aerospace, military, navigation, and air traffic control, so these devices must evolve and adapt to properly address the ever-changing requirements of the technological landscape.

The working principle of any radar involves sending out radio waves and measuring the time it takes for the waves to bounce back to the receiver after hitting an object. By analyzing this reflected signal, it's possible to determine the distance, size, and speed of the object. Typically, a radar transceiver consists of the receiver, transceiver, multifunctional antenna dish, and duplexer switch, which controls whether the Rx or Tx portions of the radio have access to the antenna.

Furthermore, a conventional radar system also requires a time-synchronization system, data processor, waveform generator, ADCs and DACs, a radio chain, and a radar display for user interface. However, traditional radars have limitations and drawbacks that affect their performance and flexibility.

Although radar systems share a common principle and electronic requirements, they come in different types and configurations, each with specific capabilities. One such type is the synthetic aperture radar (SAR), which employs radar movement to generate a virtual antenna aperture, delivering high-resolution imaging with a compact system. These systems are widely used for mapping, surveillance, and target recognition.

Doppler radar is another popular type, which uses the Doppler effect to measure the motion and direction of moving targets, in addition to their position. Doppler radar is widely used for weather forecasting and aviation, as it can detect the movement of particles and thus provide a more accurate prediction of weather events.

Finally, phased-array radars employ an array of antennas that electronically steer the radar beam, allowing for faster scanning, clutter/jamming suppression, and SNR optimization at the beam direction. They're typically used for air traffic control, military surveillance, and missile defense, thanks to their ability to track multiple targets simultaneously with high precision and accuracy. It's essential to comprehend the variations between these radar types to select the most appropriate technology for a particular application.

How to Integrate SDRs into Radar Systems

Traditional analog-based radar suffers from a fatal limitation in the modern world: It lacks flexibility and adaptability. In the current scenario, with smart software-based systems dominating electronic warfare (EW) and signals intelligence, it's crucial that radars keep up with the fast technological development to properly detect targets and protect themselves against EW attacks.

By integrating high-performance SDRs in the radar architecture, designers can take advantage of software-based functions that can be easily and remotely changed, tuned, updated, and upgraded via on-the-fly programming. There's no hardware modification and minimal human intervention.

Moreover, dynamic adaptations can be programmed to work automatically, including frequency-hopping techniques to prevent jamming and beamforming to avoid clutter. SDRs can provide a very stable and deterministic clock signal, too, which is crucial for synchronization and time reference, while also being capable of receiving external clocks from 10-MHz crystals to synchronize with other equipment in the architecture.

In terms of basic RF characteristics, SDRs can significantly improve the performance of radar systems, especially considering the very precise RFEs typically implemented in high-end SDRs. Firstly, multiple-input, multiple-output (MIMO) SDRs are fundamental for phased-array radars—typically implemented in beamforming/beamsteering techniques—and radars implementing multiple antennas for different ranges.

The best MIMO SDR in the market can provide up to 16 independent RF channels and a high level of frequency/phase stability, which allows for the implementation of synchronized antennas for complex radar techniques. High frequency range is mandatory for proper channel spacing and flexibility in terms of operation bands, which requires SDRs with wide tuning range and high instantaneous bandwidth.

Furthermore, the ability to rapidly change the main frequency can be extremely useful to avoid jamming as well as automatically adjust range according to the environmental conditions. Low noise figure and high sensitivity are critical to ensure that the radar system is able to detect weak signal reflections, especially in noisy or cluttered environments.

Together with a low noise floor (which defines the minimum detectable signal), high dynamic range is crucial to ensure that the receiver can work with high amplitudes without saturating. This makes it possible to detect cluttering and jamming without jeopardizing the operation.

High spurious-free dynamic range (SFDR) also is an important parameter, as it denotes the receiver's immunity to spurious signals. Finally, handling the massive amounts of data generated by a radar system requires high data throughput, especially when using MIMO techniques and parallel computing. High-end SDRs provide quad 40-Gb/s qSFP+ ports (upgradable to 100 Gb/s) to transmit data to the host system, minimizing data loss and overall latency.

More SDR Advantages

Modern radar techniques, such as beamforming and frequency hopping, require extensive DSP capabilities to work properly. Not only are SDRs able to satisfy the computation requirements, but they can perform these operations completely on-board, sending only pre-processed information to the host and alleviating the backhaul requirements.

Moreover, an FPGA-based digital back end brings a huge advantage over microprocessor- and ASIC-based solutions. First, the FPGA architecture enables parallel computing with very low latency, which is crucial for MIMO radars and systems that demand fast decision-making. For example, beamforming/beamsteering requires very fast parallel computation involving precise control over the phase and amplitude of the signal at each antenna element, adaptive signal processing, and proper phase synchronization.

Second, unlike ASICs, the FPGA can be completely reprogrammed to execute different operations, protocols, and DSP firmware. Furthermore, the digital back end provides on-board waveform digitization and storage, which is extremely useful for generation of pulsed waveforms, chirping, triggering, and phase-coherent waves without needing to send the waveform from the host every time.

The digital back end also can automatically control the RFE characteristics, adding another layer of flexibility to the overall architecture. For instance, digitally controlled attenuators allow the implementation of adaptative algorithms to attenuate the influence of weather in the measured signal.

In addition, sensitivity time control (STC) and sensitivity gain control (SGC) are essential in radar DSP, as they allow for gain correction to be implemented to address power losses in the transmission path. Finally, frequency-measurement DSP algorithms, such as fast Fourier transforms (FFTs), are fundamental for frequency-based radar techniques—e.g., Doppler radars—where frequency shifts must be measured to detect the target's velocity and trajectory.

Beamforming

One of the most useful modern RF techniques is beamforming, which combines several signals from multiple antennas to form a single, directional beam by synchronously adjusting the phase and amplitude of the signals at each antenna. This results in greater flexibility in directing radar coverage without having to physically move the antenna, providing maximum sensitivity in a certain direction and rejecting the jamming and clutter signals from unwanted sources.

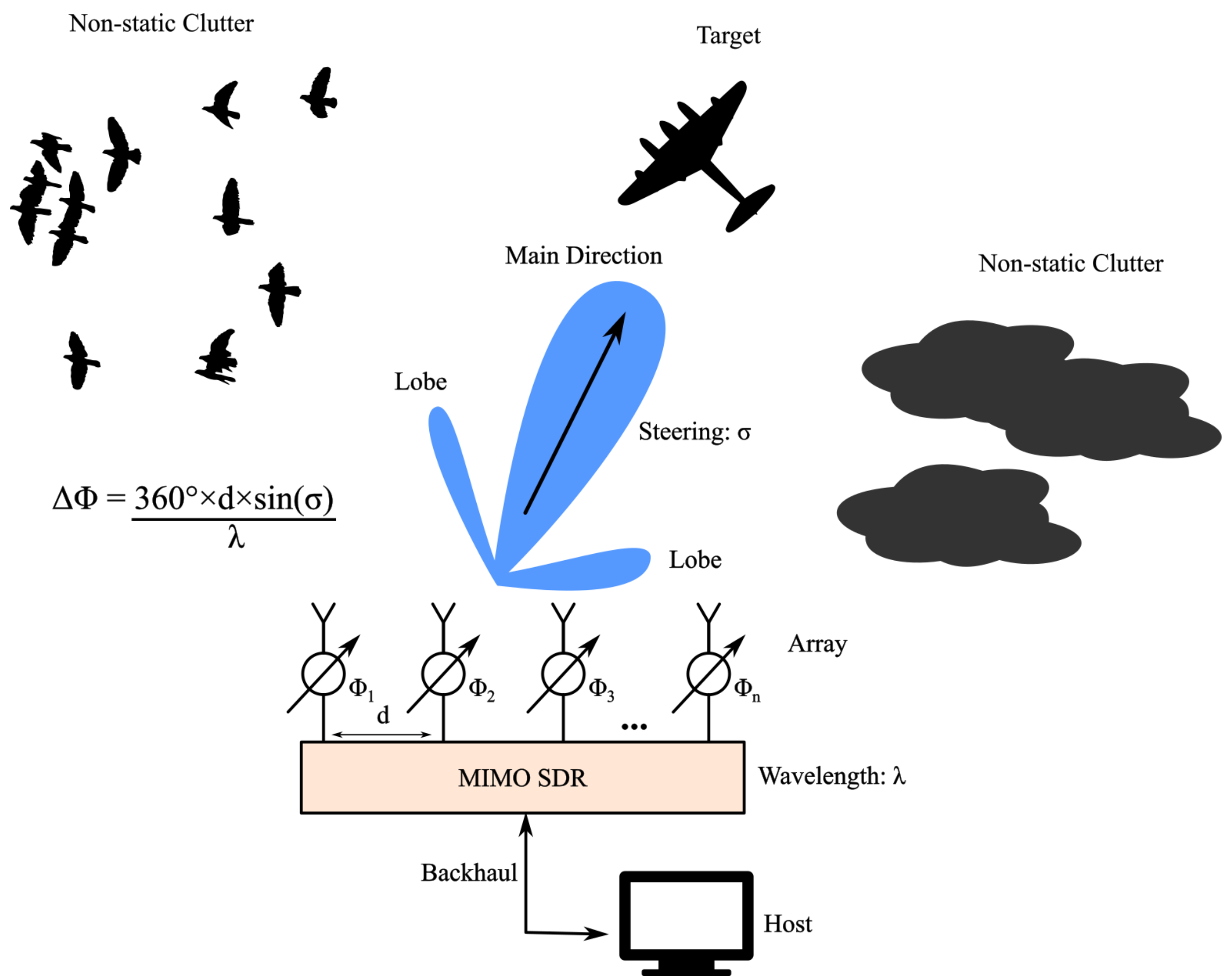
However, controlling the array's radiation pattern by adjusting the phase of each antenna isn't an easy task—it requires heavy parallel computation of MIMO channels with minimum latency. Barring that, phase coherency can't be achieved, and the radar loses control of the beam.

In an SDR system, the FPGA performs all of the necessary calculations to control the phase and amplitude of each antenna element in real-time. This allows for rapid updates to the beam direction and shape and ensures enough agility to properly follow the target.

From the diagram in *Figure 2*, note that the angle of steering depends on the distance between antennas and the wavelength of the signal, and the phase difference between each element of the array. The wavelength is typically defined by regulations and range, while the distance between elements is limited by physical constraints.

Thus, the steering angle is controlled by the phase difference, and that's why phase and frequency stability are so important in this application. Furthermore, the phase difference for a certain angle, as well as the timing required to achieve this difference at each waveform generator, must be calculated onboard the FPGA with minimum latency.

Modular SDRs—especially those implementing MIMO transceivers—can be implemented as "all-in-one" solutions. As a result, commercial off-the-shelf (COTS) modular SDRs could significantly reduce the overall complexity and design cost of a radar system. This is because a single SDR can implement multiple functions in the same unit, including Rx/Tx operation, telemetry, and self-calibration.



2. In a MIMO SDR system, the FPGA performs all necessary calculations to control the phase and amplitude of each antenna element in real-time, allowing for rapid updates to the beam direction and shape and ensuring enough agility to properly follow the target.

In addition, the interoperability of SDRs makes it possible to use them in older or existing legacy radar systems, enabling service-life extension programs with minimum hardware modification. Because most of the functions are implemented in the software domain, SDR-based radars are completely future-proof. That means the transceiver can be upgraded or completely repurposed with minimum intervention, requiring only the upload of a new program.

Thus, the radar can always be up-to-date with the latest protocols and techniques, enabling SDRs to significantly reduce the long-term costs of a system by reducing the need for manual maintenance, component count, system complexity, and engineering/deployment time. On top of that, using an SDR can lead to SWaP reductions, making it an attractive option for critical applications, including light aircraft radars and satellite systems.

Conclusion

Software-defined radio offers a flexible and cost-effective solution for modern radar systems. By utilizing high-performance RFEs combined with FPGA-based digital backends, these transceivers can perform a wide range of embedded DSP functions, including waveform generation, modulation/demodulation, data packaging, mixing, and pulse compression.

The RFE can satisfy all the RF requirements of modern radios, including wide tuning range, MIMO operation, low noise figure, and high dynamic range. The digital back end enables the implementation of complex radar algorithms and techniques, including beamforming and frequency hopping, in a future-proof solution.

The modular and scalable nature of SDRs also allows for interoperability with existing legacy systems, while enabling future upgrades and customizations with minimal costs. Moreover, SDRs can reduce the complexity and overall SWaP of radar devices, suiting them for applications ranging from defense and surveillance to weather monitoring and aviation.

Kaue Morcelles is an electrical engineer with emphasis on electronic design and instrumentation. He currently works with biomedical research, developing instrumentation devices for tissue engineering. Learning and writing about cutting-edge technologies is one of his passions, along with coffee, musical instruments, and weird animals.