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Yan (Rockee) Zhang, Jorge Salazar Cerreno, Christopher Bassett, Keith Kelly, "Simultaneous multi-mission (SMM) in ground and airborne radars: system development tools and enabling technologies," Proc. SPIE 11003, Radar Sensor Technology XXIII, 1100307 (3 May 2019); doi: 10.1117/12.2518430

Event: SPIE Defense + Commercial Sensing, 2019, Baltimore, Maryland, United States

Simultaneous Multi-Mission (SMM) in Ground and Airborne Radars: System Development Tools and Enabling Technologies

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There is a significant need for portable, low-cost, and multi-functional ground and airborne radars. In some applications, the goal is to integrate multiple functions within a limited and constrained frequency band. For other applications, however, the challenge is how to support multiple missions that have been associated with separated frequency bands. This study considers the feasibility of two possible solutions for multifunction radar: the multi-band, agile frequency diversity radar, and a broad-band, common radar aperture. For either of the solutions, the goal is to find the optimal architectures and enabling technologies that support the integration of the following mission requirements: (1) automatic precise landing support, (2) counter-threat detection (such as counter-drone) in ground and airborne operations, (3) 3D-altitude-finding, (4) portable local weather surveillance. We investigated the basic requirements of each of these missions and summarized the trade analysis results. Next, we investigated the current enabling technologies for two proposed aperture options, especially regarding the design of radiating elements. Multiple antenna element designs were studied, which show promise for meeting multi-band or broadband aperture needs. A simulation verification based on the Phased Array System Simulator (PASIM) technology, which was jointly developed with MathWorks, is introduced. The simulation serves as a method to evaluate the quality of performance (QoP) of different radar missions that can be achieved with specific architectures. We investigated a mixed-signal transceiver and GPU-enabled backend software system that allows for the parallel execution of multiple radar missions through the same aperture.

1. INTRODUCTION

The need of multi-mission radars has been significant for the past decade, government programs in FAA (such as the MPAR), NOAA, DoD/DARPA and industries have established foundations for potential systems that perform functions of surveillance, tracking, imaging and navigation. Following this trend, we are currently investigating a newer generation of multi-mission radar system, which aims to address some issues raised for previous multi-mission radar developments, such as:

- Currently, the primary way to achieve multi-mission is mostly based on repurposing the existing system hardware to measure other types of phenomenon. For example, "core mission" maybe small target tracking and then the "extended" mission is weather observation. Because of the lack of system planning and standardization, usually the performance of some missions is sacrificed to ensure the normal performance of the core mission. Such an arrangement also adds a lot of challenges for modifications of the existing hardware and firmware.

- Some of the designs only focused on applying high-end semiconductor technologies or markets but ignored the specific requirements for different missions. The assumption that a "universal software-defined radar" can be reconfigured for all the possible mission is risky in term of cost, performance, power consumption and scalability,

Radar Sensor Technology XXIII, edited by Kenneth I. Ranney, Armin Doerry, Proc. of SPIE Vol. 11003,
1100307 · © 2019 SPIE · CCC code: 0277-786X/19/$18 · doi: 10.1117/12.2518430

since the commercial general-purpose chipset may fall short of specific performance to support a certain type of radar operation.

- Comparisons and optimizations of using different radiating elements, different apertures and scan schemes for different radar functions. Such studies ("trade analysis") are best done through simulations. However, the current capabilities of simulations are not well-suitable for the purpose. For example, the target models, as well as the processing chain for hard target, are quite different from distributed targets. Current design procedures usually focus on enforcing the phased array antenna to generate types of radiation patterns that match the existing radars, but lack of more in-depth analysis and comparison of advantage and disadvantage of individual apertures.

- Existing developments of multi-mission hardware emphasizes the reconfigurability with the hope of switching the operational functions to support different users. In reality, the concurrence of missions (such as simultaneous tracking of multiple targets, need of multiple beams for aircraft or weather surveillance, and more stringent requirements for real-time processing) needs further explorations beyond shared apertures, such as multiple functions executions in the same aperture with the same slot of radar job period.

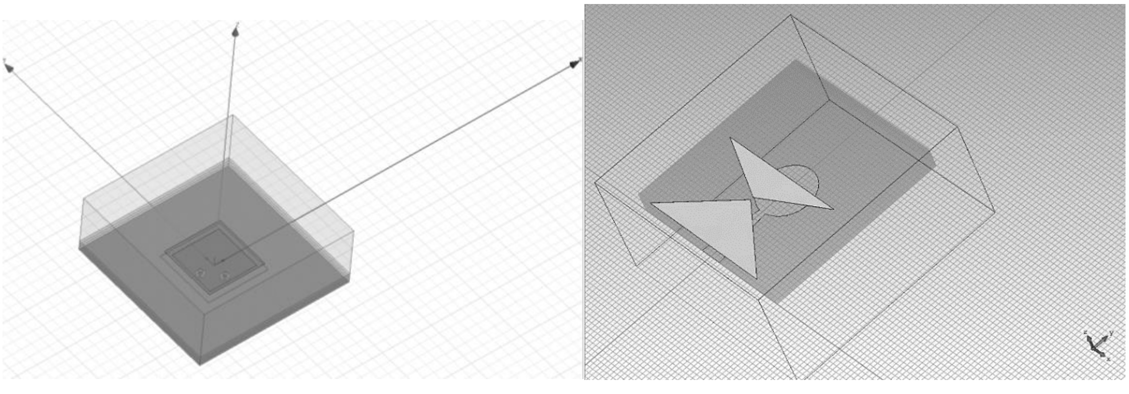
As a specific example, we consider conceptual and system design of a future low-cost radar that supports multiple missions simultaneously, which address the need for mobile, battle-field airport operation and low-altitude surveillance surrounding. This system is expected to execute the functions simultaneously (i.e., information must be updated at each volume coverage interval (VCI), which is assumed to be nominally 4-5 seconds): (1) Automatic precise landing support, for precise approach radar (PAR) support of incoming friendly aircrafts, (2) counter low-altitude threat operation (such as counter-drone) at low-altitudes, (3) 3D-altitude-finding, (4) local-area weather surveillance and hazard detection.

These new challenges motivate us to investigate novel engineering ideas behind the so-called Simultaneous Multi-Mission (SMM). The goal of this initial investigation is to establish a new multi-mission phased array radar architecture and path to a future radar product that addresses the above challenges with low-cost, agility and intelligence. We used the ongoing development of a counter-drone system as an example and introduced some initial solutions and evaluations in the following sections. The system is referred to as "SMM-A" in this paper and most of the parameters are generic.

2. SMM TECHNOLOGIES

2.1 Radiating elements

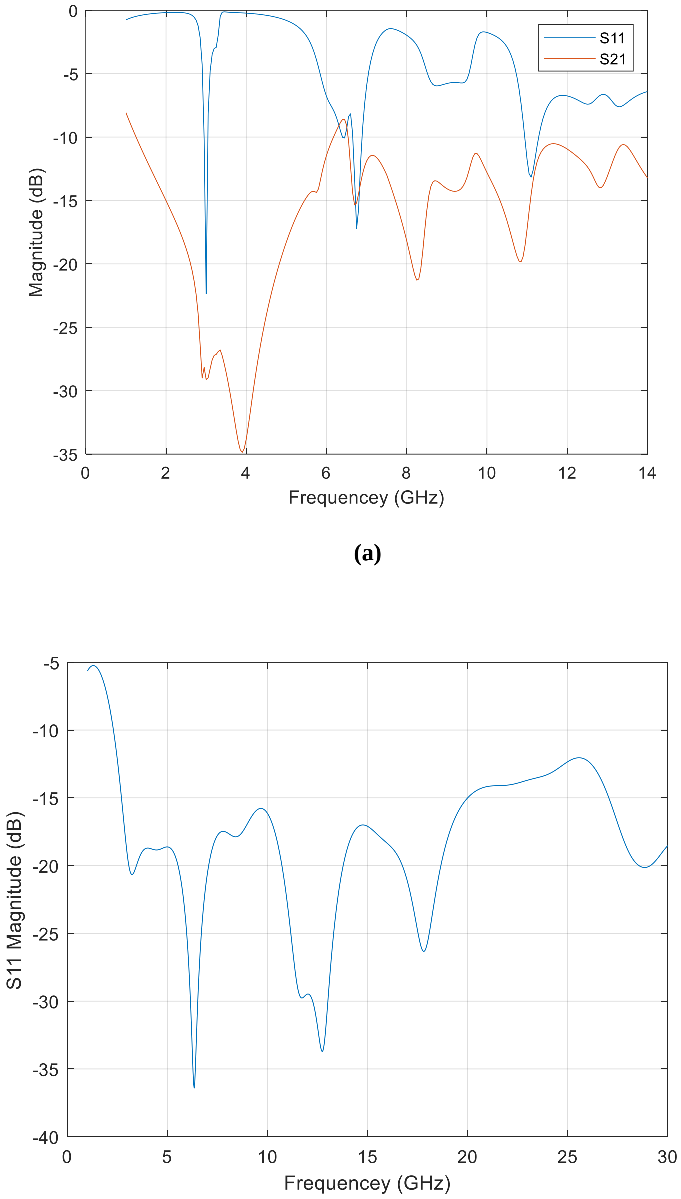
SMM radar intends to maximize the usage of spectrum resources from UHF to Ku-Band, with emphasizes on the key radar operating frequency bands (L, S, C, X, and Ku). Radiating elements that meet these challenges are the specific multiband resonating elements (example shown in Figure 1(a)) and ultra-wideband radiating elements. Figure 1(b) shows a recently designed multi-layer "tow tie" UWB element to support SMM.



(a) **(b)**

Figure 1: Different radiating element designs for SMM (a) Multi-layer, dual-polarized patch element, (b) Ultra-wideband (UWB) bow-tie radiating element. Both elements are designed by engineers from OU-IART.

The multi-band return loss for the square patch (Figure 2(a)) is compared to the UWB return loss (Figure 2(b)). As shown in the plots, the patch is optimized to resonate at specific frequencies (e.g., 2.4 GHz, 5.6 GHz and 11 GHz). At these specific frequencies (sometimes called TMn0 modes), the return loss can be better than the UWB response. However, the UWB responses cover broader ranges of frequencies with less need for numeric design optimization.



(a)

(b)

Figure 2: (a) Sample S-parameters of the dual-polarized patch operating in multi-band mode. (b) Sample S-parameters of the ultra-wideband

Comparisons of gains over frequencies also show some interesting results. The single element of multi-band patch and UWB elements may be designed to have similar gains over frequencies. Overall speaking, the UWB option seems more flexible to apply and easier to design.

2.2 Hybrid mode scanning aperture

As the multi-band aperture can reuse element designs like MPAR, it is more natural to use it in a larger aperture or a mix of different apertures. Dual-polarization is also supported using this approach because the multi-layer patch designs already have such capability. Figure 3(a) shows one of the systems that use dual-band radiation (S and C Bands) on a multi-facet array. The S-Band radiation beams are used for search function and C-Band beams are used for track. The two missions can be executed through the same aperture simultaneously without mutual interference. The aperture size would be large (to achieve 1-2 deg beamwidth) for larger scale surveillance and tracking.

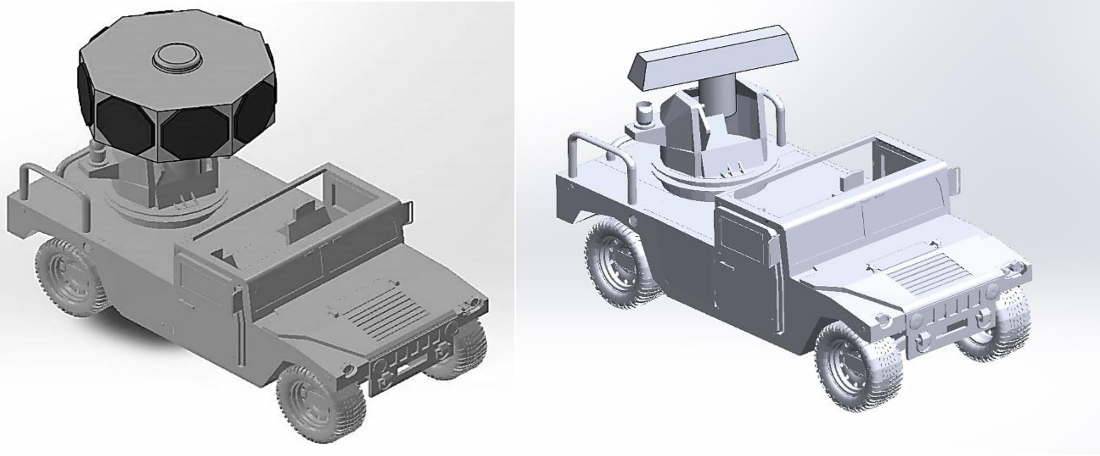


Figure 3: A conceptual depiction of how the heterogeneous apertures are combined into one system for SMM based on multi-band radiators. (a) A larger, ground-based surveillance radar with multiple fixed facets, (b) A smaller, hybrid scanning radar mounted on a generic truck/vehicle based on UWB aperture.

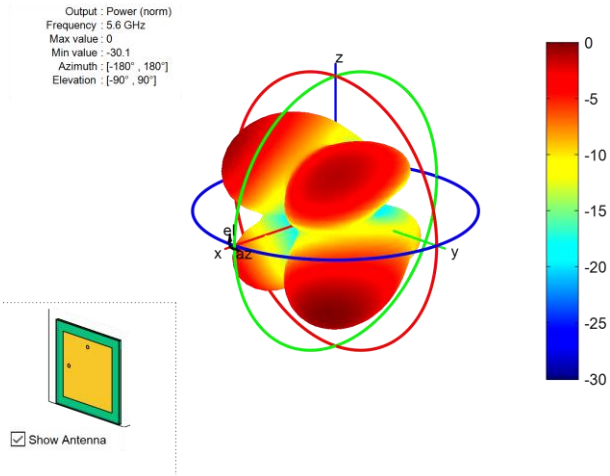
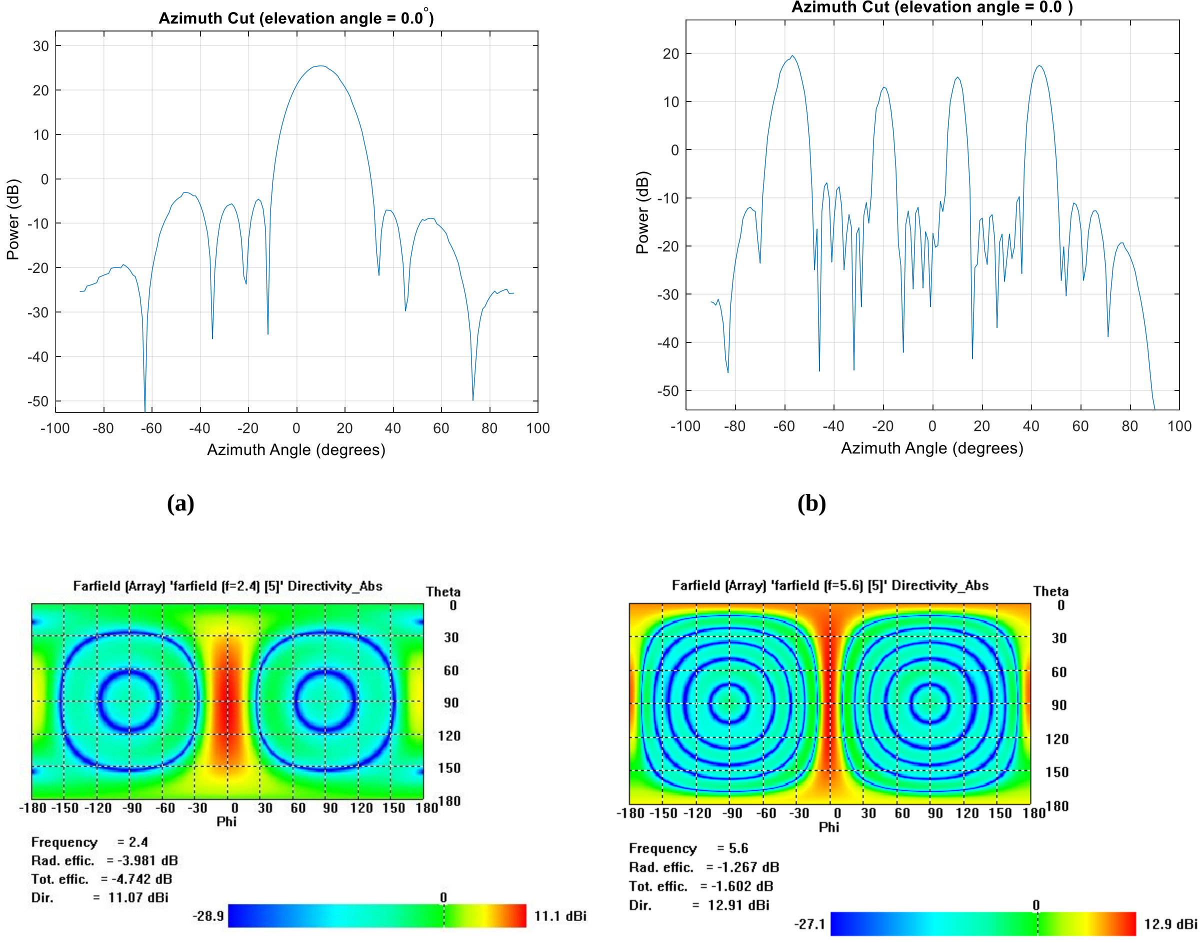


Figure 4: Isolated element pattern of a simple dual-polarized patch antenna at TM20 mode.

Naturally, operating at multi-band mode and higher excitation modes will produce pattern distortions from element level to array levels. Figure 4 shows the element pattern of a single dual-pol patch excited at TM20 mode (5.6 GHz), which is quite different from the TM10 base mode pattern.

We expect UWB element is more suitable for a shorter range SMM implementation. In the potential application of low altitude air-surveillance, it is populated as a thinned array lattice, and then mounted on a rotary spinner. The azimuth scan is then based on mechanical pointing and elevation scan is electronic.

At the array level, the variation of patterns for different frequency bands are also the main challenge. In Figure 5 we show examples of array patterns for multiband and UWB arrays. We can clearly see the “grating lobes” emerging when the multiband array steers the beam off boresight. For UWB array, beamwidth variations and slight gain variations are expected.



(a)

(b)

(c)

(d)

Figure 5: Array-level pattern and ambiguities. (a) Steering of 8 by 8 rectangular array using multi-layer patched element to 10 deg azimuth, excited at 2.4 GHz. (b) 8 by 8 rectangular array using multi-layer patched element to 10 deg azimuth, excited at 9.4 GHz. (c) UWB element linear array pattern (8 by 1), excited at 2.4 GHz, (d) UWB element linear array pattern (8 by 1), excited at 5.6 GHz.

A “pattern normalization” technique is being developed, which can resolve the spatial ambiguity and variations caused by different frequency modes. The technique requires precise knowledge of the 3D patterns at multiple frequencies and that the target is a “simple point target”. More details of the approach will be reported in other publications.

2.3 Front-end TR Modules

SMM architecture requires each operating band has own set of electronics since the integrated microwave components on the market are limited to specific frequency bands. Multi-band components are however emerging, such as filters [ref]. It is envisioned that different TRM “cards” will be used behind the same aperture and operate at different bands simultaneously. An example of S-band “card” initial prototype is shown in Figure 6. This card holds 8 channels of TR modules based on commercial chipsets.

Figure 6: Front-end module “card” developed by OU-IART/ARRC [5], supports S-band operations.

2.3 SMM backend

Generic backend system architecture for SMM is shown in Figure 7 and one of the initial implementations was discussed in [6]. There are a few highlights in the diagram that emphasizes (1) The low-cost, PC-based system will be the platform for the execution of the data processing and radar job management. (2) PCI Express (PCIe) will be used as the system backend protocol rather than RapidIO because of the better industry adoption trend and availability of supports.

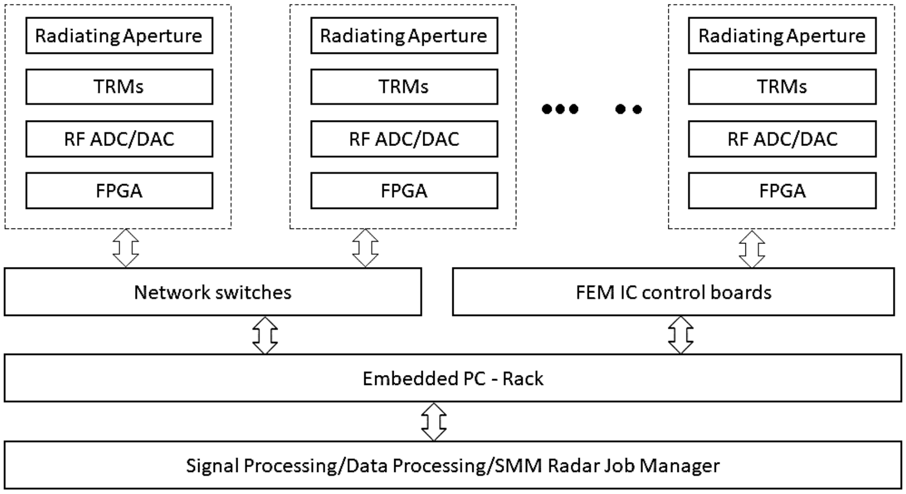


Figure 7: SMM backend: generic structure

The backend software system can run on common PC platforms, which executes signal processing, data processing and radar job management. Radar management for SMM is based on a resource mapping table that connects the selection of radiation aperture, frequency of operation, and the radar missions (such as target search, target track, weather surveillance). General parameters for the mission schedule are listed in Table 1.

Table 1: The key parameters for multi-mission scheduling

System job parameters	Meaning
F_H	Horizontal field of view in degs
F_v	Vertical field of view in degs
θ_{az}	Azimuth beamwidth in degs
θ_{el}	Elevation beamwidth in degs
T_{dwell}	Dwell time for each search job beam position (s)
PRT	PRT of transmit pulse waveform (s)
$T_{confirm}$	Time required for confirmation job (s)
T_r	Revisit time interval for confirmed target for track (s)
T_{track}	Time required for tracking job (s)
f_{search}	Fraction of radar resource for search
$f_{confirm}$	Fraction of radar resource for target confirmation
f_{track}	Fraction of radar resources for tracking

The conventional high-level equations that govern the total surveillance time (represented by the total volume coverage time, T_{volume}) are given by:

$$T_{volume} = \frac{\frac{F_H}{\theta_{az}} \cdot \frac{F_V}{\theta_{el}} \cdot T_{dwell}}{f_{search}} \qquad (1)$$

$$f_{search} + f_{confirmation} + f_{track} = 100\% \qquad (2)$$

The proposed SMM system will allow for reduction of the T_{volume} by coverage of a spatial volume with multiple beams simultaneously from multiple frequencies. Parallelized processing channels at the receiver separate multiple frequencies and process each band individually. Thus, transmitter is preferred to be UWB while receivers can be either MB or UWB. The combination of the mechanical scanning and electronic scan at elevation would use management algorithms similar to [3].

3. SYSTEM SIMULATION AND VERIFICATION

3.1 System simulation method

Simulations of initial SMM designs can support the investigations of system trade analysis and Impact of antenna element designs on the mission performance. Simulation is mainly performed based using MATLAB tool, with the basic structure shown in Figure 8. There are some unique features of the simulation developments. (1) For both MB and UWB options, the simulation can load the realistic aperture radiation patterns into the environments for evaluations. (2) The simulation follows time-domain modeling of all system components, including electronics [4], waveform and pulse compressions. (3) Including the target environment factors such as clutters and target micro-Doppler signatures. (4) Simulation is based on Monte-Carlo runs, so the performance can be evaluated based on comparing theoretical and statistical results.

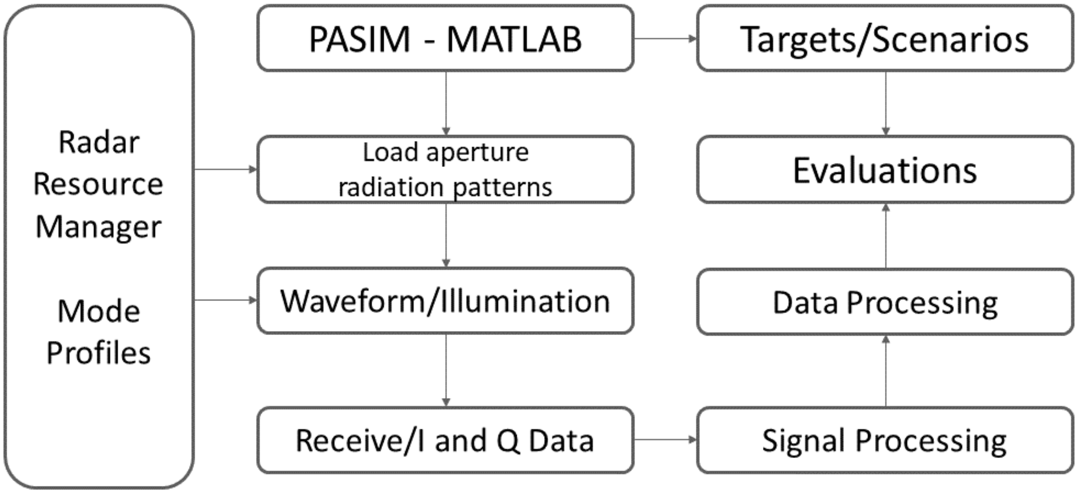
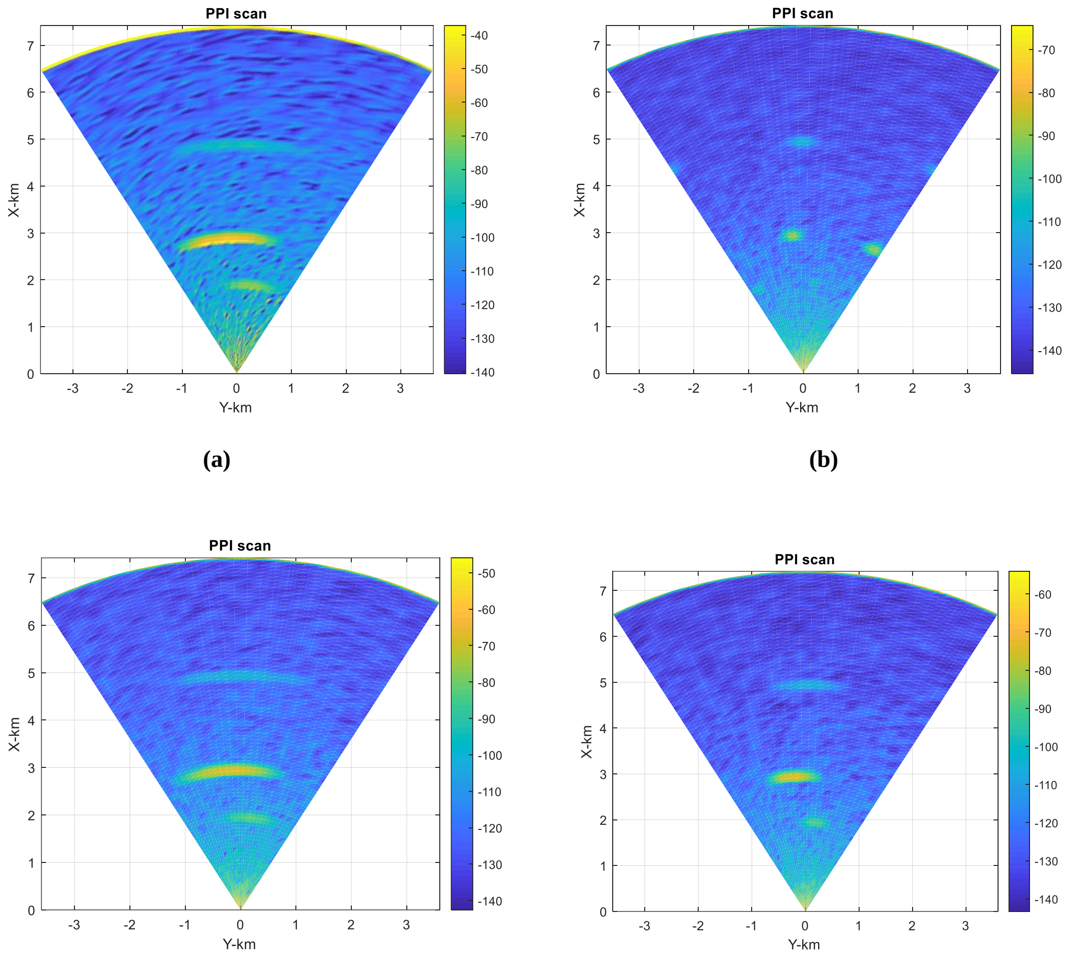


Figure 8: System simulation and evaluation for SMM

3.2 Preliminary and Sample Results

Some of the initial simulation results for the drone detection scenario are shown in Figure 9 and 10. The examples in Figure 9 show the 2D PPI scan of three small drone targets at different ranges (2 km, 3 km and 5km). For each scan, we used different array apertures in the simulations. For example, the Figure 9 (a) and (b) display the scans using multi-layer patched element apertures operating at two frequency modes (5.6 and 9.4 GHz), whereas Figure 9 (c) and (d) display the scans using ultra-wideband apertures based on the bowtie element. Both apertures are simple 8 by 8 rectangular lattices.



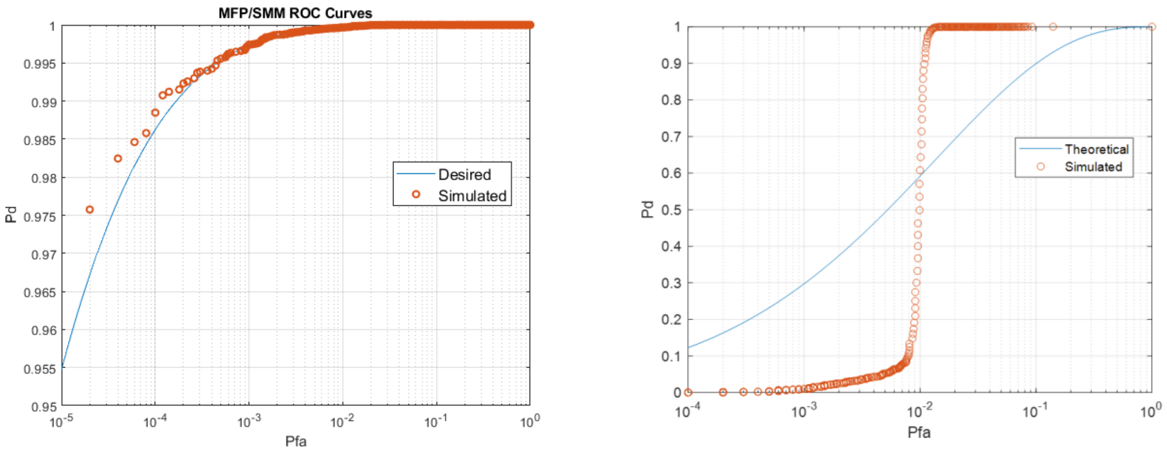
(a) (b)

(c) (d)

Figure 9: Simulation of electronic scan PPI with "hovering" drone targets with a "generic" SMM radar sensor. (a) MB aperture scan operating at 5.6 GHz. (b) MB aperture scan operating at 9.4 GHz. (c) UWB aperture scan operating at 5.6 GHz, (d) UWB aperture scan operating at 9.4 GHz.

In addition, terrain clutter models are added in both results. As expected, the multi-band (MB) scans show better angular resolutions at the higher frequency band than the UWB aperture, while also lead to ambiguities. The UWB aperture results demonstrate more stable target signatures at different bands.

Figure 10 shows some sample results for radar operating curve (ROC) using different waveforms. Assuming similar transmit waveform bandwidths (resulting in 10 m range resolution) are applied and similar dwell time (or time-on-target) are assumed. Interestingly, the ROC from the pulsed LFM waveform shows matching between theoretical curve and simulation. However, the ROC from the FMCW shows differences. Actual detection performance based on using FMCW waveform depends on more factors such as spectrum estimation algorithms and target velocities. Overall, similar detection performance would be achieved for both waveforms if similar backend resources are used.



(a) (b)

Figure 10: Radar operating curve (ROC) of small drone target using X-band aperture. Assuming similar hardware and transmit signal bandwidth is used. (a) Pulsed linear frequency modulation (LFM) waveform, (b) wideband FMCW waveform.

4. CONCLUSIONS

The novelty of the SMM system concept lies in executing simultaneous radar functions through multiple frequency bands. This work provides high-level considerations of designing and implementation of an SMM system for the counter-drone type of applications. The primary focus of the study is comparing the multiband (MB) and ultra-wideband (UWB) options, including radiating elements, apertures, TR module technologies, and waveforms. Preliminary system simulation results based on the end-to-end Monte-Carlo simulation method are discussed. It is shown that both MB and UWB solutions can potentially meet the mission requirements with similar costs. The MB solution is more appropriate for lower frequency band surveillance missions, while UWB is more appropriate for higher-frequency (C to Ku band) precise tracking functions. A common backend system, which is based on the software-defined radar (SDR), can support both categories of operations.

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