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Search optimization for minimum load under detection performance constraints in multi-function phased array radars

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A B S T R A C T

This paper presents a solution procedure of surveillance parameter optimization to achieve minimum radar load while ensuring desired one-off and cumulative probabilities of detection in a multi-function phased array radar. The key approach is to convert the nonlinear optimization on four search parameters – beam width, beam spacing ratio, dwell time, and frame time – into a scalar optimization on signal-to-noise ratio by a semi-analytic procedure based on subproblem decomposition, which improves computational efficiency of the optimization process as well as facilitates physical interpretation of the optimized parameters. The efficacy of the proposed solution approach is verified with theoretical analysis and numerical case study on an airborne phased array radar.

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1. Introduction

In a phased array radar, a beam is electronically steered and time for the steering is of the order of microseconds [20]. This capability facilitates the use of it as a multi-function radar that alternately performs tasks of various functions such as search, confirm, track, and fire control. Since radar resources (such as time and energy) are limited, it is necessary to effectively allocate/distribute these resources to multiple functions and tasks to maximize overall mission performance (see [7,11,12,18,24,25,9,2,8] for various approaches to multi-function radar resource management).

One key problem in this resource allocation is search optimization that determines parameters of search beam and pattern to achieve (or enhance) search performance while spending minimal amount of radar resources; thus, it is inherently multi-objective and trade-off between the search performance and the radar resource consumption is required. Typical measures for search performance are metrics of target detection performance including one-off/cumulative probability of detection and detection ranges, while a search load, defined by the ratio of radar time allotted for search function, is typically used as a metric of temporal resource consumption. The specific formulation of this multi-objective decision may depend on the operational policy of the radar. In case other radar functions/tasks have absolute preference over surveillance, a typical formulation is to maximize the performance under constraints on the resource consumption, while a formulation of minimizing the resource consumption under performance constraints can be more effective to incorporate preferential search requirement (e.g., to search for unidentified threats).

The search performance can be influenced by various search beam parameters and the shape of the search beam lattice. While the choice of lattice types (i.e., triangular versus rectangular) was known not to produce significant difference in performance in terms of overall energy loss [14] and detection probability [10], selection of beam parameters can make a significant impact on the performance of the radar search function. Hence, many previous researches have addressed optimization and/or sensitivity studies on these parameters for single-function search radars [16,14,17] and also for multi-function radars [4,5,26,13].

Most of the previous work utilized numerical or graphical optimization for various search parameters [16,14,4,5]. Early work in [16] investigated optimal frame time of a search radar which maximized detection range for a given cumulative probability of detection. Optimal beam spacing in terms of beam shape/packing loss that can be interpreted as required energy consumption was studied in [14]. The same approach to parameter optimization for search function of phased array radar was introduced in [4], and false alarm probability, frame time, beam spacing, and duty factor were used as parameters in the design process. System properties of a radar are adjustable in the design process, thus the objective function of the optimization in [4] was relative required power, instead of target detection performances, guaranteeing specified

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track initiation range. In [5], track initiation range, 50% detection range, and relative required power with respect to frame time, dwell time, and beam spacing were studied.

However, the approaches described in the previous paragraph cannot be directly applied to the context of resource management for multi-function radars. The resource management issue that is crucial for operation of a multi-function radar was not considered in [4,5]; the optimization approaches in these studies were for design rather than operation of a radar. For a multi-function radar, differing from a single dedicated function radar, radar resources can be preferentially distributed to higher priority functions than the search function, especially in multi-target tracking or fire control during an engagement. Thus, constraints/limitations of radar resources available for the search function should be explicitly taken into account. Recent studies [26,13] were devoted to search parameter optimization with consideration of the concept of radar search load. In [13], frame time, signal-to-noise ratio (SNR), and beam overlap angle were optimized to reduce search load while required track initiation range was maintained. Search load that consists of time and power load, both of which are functions of dwell time and frame time, was presented in [26], and the parameters were optimized to maximize track initiation range under the constraint of specified search load. In the same way as the researches in the previous paragraph, numerical optimizations were applied to the both studies [26,13].

It should be noted that availability of analytic solutions for search optimization is very limited. For a missile approach-warning radar system in which full resources are dedicated to the search function, an analytic solution for optimization with a single design variable, dwell time, was presented in [17]. In the process of deriving the analytic solution, [17] also confirmed the numerical results in old literature [16] on the generalization of range interval for averaged single-scan probability detection.

In this paper, a semi-analytic optimization procedure of surveillance beam parameters of multi-function phased array radars is presented for minimization of search load while keeping desired one-off and cumulative probabilities of detection. Beam width, dwell time, beam spacing ratio, and frame time are included in the beam parameters. The major finding of this work is that the optimization problem can be decomposed into a set of three subproblems, thus the procedure is threefold:

1. analytical optimization of beam width, dwell time, and beam spacing ratio with a certain level of SNR;
2. root-finding with respect to frame time with a certain level of SNR;
3. one-dimensional numerical optimization of search load along SNR using optimal beam parameters attained in the previous steps.

Since analytic expressions of three beam parameters are available from the first step, the nonlinear constrained optimization with respect to four variables is reduced to a line search problem of a single variable, i.e., SNR, including iterations of one-dimensional root-finding. Equivalence of this subproblem-decomposition-based approach to the original nonlinear optimization is shown in the process; numerical results verify the efficacy of the proposed method.

A preliminary version of this work was presented in [15], but it addressed only one of the subproblems in this paper. This paper exclusively includes: (a) optimization procedure including an additional parameter (i.e. frame time) and a constraint (i.e. cumulative probabilities of detection), (b) more theoretical analysis on analytic optimization of the first subproblem.

The rest of the paper is organized as follows: Section 2 formulates the search optimization problem by defining the design variables of search parameters, constraints on detection performance, and the cost function of radar load; in Section 3, the decomposition of the optimization problem and respective solutions of the subproblems are presented; Section 4 demonstrates the optimization procedure with numerical results; the paper is concluded in Section 5.

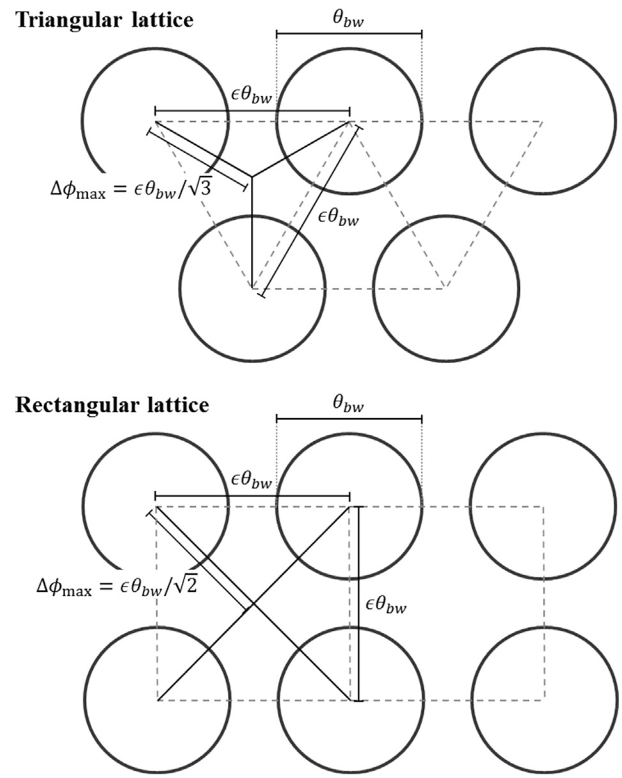

Fig. 1. The maximum target deviations from beam boresights in triangular/rectangular lattices.

2. Problem description

2.1. Search beam parameters and radar load measure

Consider search beam patterns of triangular and rectangular lattices (Fig. 1). The design variables for the optimization are search beam parameters that decide the pattern and execution of the beams:

- *Beam Width* (θ_{bw}): The effective width of the radar beam.
- *Beam Spacing Ratio* (ϵ): Angular distance between adjacent beams normalized by the beam width.
- *Dwell Time* (t_d): Execution time of a search task for a single beam position.
- *Frame Time* (t_f): Execution period of a search frame, which is a group of beams forming a lattice in an assigned search area.

Dimensionless variables associated with the above design variables can also be defined for convenience of analysis:

$$r_\theta := \theta_{bw}/\theta_{bw,0} \tag{1}$$

$$r_d := t_d/t_{d,0} \tag{2}$$

$$r_f := t_f/t_{f,0} \tag{3}$$

where variables with subscript 0 denote some reference values. The beam spacing ratio ϵ is by definition dimensionless. The use of these dimensionless variables allows an analysis regardless of the specific values of corresponding radar properties, and it produces

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