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Scheduling Methods for a Conformal, Phased Array Multifunction Radar

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***Abstract*— This paper presents a method for the scheduling of a multifunction radar based on an active phased array of the conformal type (frustum of cone). This type of antenna obtains a 360 degrees horizontal coverage by a number M of sectors each one belonging to a sub-array, where different non overlapping sub-arrays can illuminate different targets at the same time. This operation has both the advantages of a rotating antenna and those of the electronic scan of a fixed-faces multifunction radar. In this context, a scheduling algorithm has to organize a number of parallel radar tasks respecting the constrains on the update intervals. The goal is to implement a scheduling algorithm for a system quite similar to a fixed-faces multifunction phased array radar, with the significant difference that the faces number and pointing directions are variable and adaptive to the scenario. An optimization model is presented and then a heuristic models is discussed with some computational results.**

***Keywords*—tasks scheduling, multifunction radar, conformal array**

I. Introduction

A multifunction array radar (MFAR) can perform the several functions generally performed by a number of dedicated radars: surveillance, tracking, weapon guidance, navigation, communication etc. The design of such a radar system implies trade-offs, first of all the choice of the RF frequency, the choice between passive or active, single or multiple array, rotating antenna or fixed faces. An MFAR can be employed in the civil field, the most common application being for air traffic and weather control, or in the military field, as part of a defence system. More details about the MFAR concept and design can be found in [1] and [2]. A careful design and implementation are needed to optimize the radar functionalities performance. In this context the control and managemnt of the radar resources (time and energy) is of fundamental importance. Within the radar resources management, the scheduling, to which the time allocation of the radar tasks is demanded, is the concluding part of the process.

Developing a reliable scheduling is a well known problem, of strong interest also in other fields like industry or information processing and transmission, and a wide literature is available. References [3]-[12], with a general survey on the radar tasks scheduling problem, report a wide set of linear program or heuristic methods to maximize the number of scheduled tasks respecting time constrains.

In this paper we propose a scheduling algorithm for a conformal array multifunction radar with some substantial differences with respect to a rotating antenna and to a fixed-faces radar.

The considered MFAR can be conceived as a dynamic-multi-faces radar in the sense that at any time one or more different faces can be defined with different pointing. This concept is described in the following paragraph, while in paragraph III an optimization model is shown based on heuristic methods. The solution is obtained operating a limited time-shift of the starting times of the tasks and/or a dwell-time reduction, whenever needed. Finally in paragraph IV some simulated trials are presented to show the performance in a given scenario.

II. The multifunction radar architecture

In this work we considered a multifunction radar called d-Radar and based on a conformal array with radiating elements or “columns” allocated on the surface of a frustum of cone. A bistatic architecture of this system, patented [13], is presented in [14] and [15]. In this paper we consider, for the sake of clearness, a monostatic simplified version, as the particular architecture does not influence our basic results. The d-Radar antenna can be seen as a sequence of tilted columns (each one being a uniform linear array), constituting a conical radiating structure. It is possible to define a sub-array by grouping a number of adjacent columns, as shown in Figure 1. The transmission and reception to a defined direction is obtained with a set of columns such that the perpendicular line to the central column points at the desired azimuth. The pointing in elevation is obtained by the appropriate phase difference between the elements on the columns.

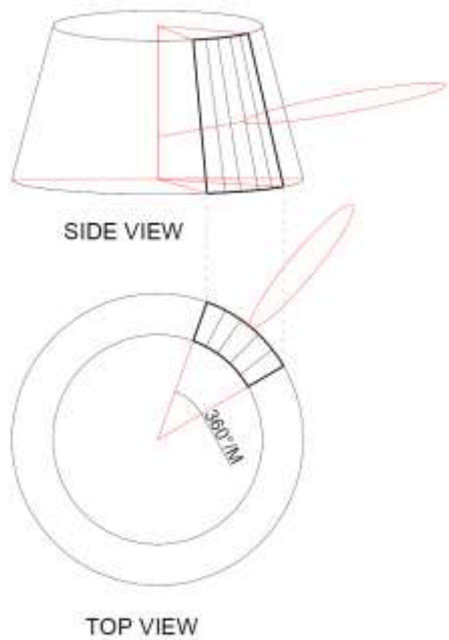

Figure 1. Conformal array (frustum of cone)

The advantage with the respect to a fixed-faces phased array radar is that each sub-array transmits and receives on the boresight, avoiding the beam widening and the loss of gain due to the scan angle of the conventional electronic steering. Digital beam forming (DBF) is extensively used in d-Radar. The beam-shape properties depend on the number of columns used to define the sub-array, that can be dynamically set without limitations apart the constrains on elements coupling and on the array element radiation pattern. The discussion on the optimal setting of sub-arrays definition depend also on the total number of columns, on the cone diameter and tilt, on the wavelength and other elements, but it is not the aim of this paper. Different non overlapping sub-arrays can transmit and receive simultaneously (in reception, overlapped subarrays may be formed but this is not considered in this paper). In a more general view of the system the number M of sub-array is time varying and adaptive with the scenario and with the set of radar functions to be executed. To better understand the concept suppose that the search function has to be executed in a defined solid angle. Hence, it is convenient to define a number M of sub-array with equal characteristics, by a partition of the antenna columns into M equal subsets. Two examples follow:

i) For a search over the full hemisphere, each subarray '*looks*' at its own azimuth boresight with *360/M* degrees difference with respect to the adjacent one. The elementary step of the azimuth scan is obtained when each sub-array takes the last column of the contiguous one. In this way M lobes "scan" together the search solid angle. Figure 2 shows, on a simplified architecture (15 columns, 5 sub-arrays each one composed by three columns), the concept of azimuthal scan and the concept of multiple beams for the search function.

ii) With this second example, we consider the dedicated tracking of multiple targets. The number and the characteristics (n. of columns) of the sub-arrays is defined in accordance with the spatial distribution of the targets. Different targets with a significant azimuth distance can be illuminated by different sub-arrays simultaneously. On the other hand, if the targets are too close consecutives illuminations are necessary using two sub-array with a large degree of common columns (less is the azimuth distance, more are the common columns). Figure 3 shows the concept: targets #1 and #3 can be illuminated simultaneously by two non overlapping sub-arrays, target #2 is illuminated later by a sub-array which would been overlapped with the target #1 sub-array.

Imagine that the radar has to perform different types of functions (i.e. close range search, long range search, tracking etc.), each one requiring its own update interval. Then, at any given time, it is necessary to manage several activities (depending on the number of active functions, on the scenario and on the coverage volume), to decide the proper antenna partitioning with the optimal sub-arrays number M and finally the execution times, respecting the update intervals. This is a general radar tasks scheduling problem with the additional challenge being on the search of the proper antenna division that allows the best resources exploitation.

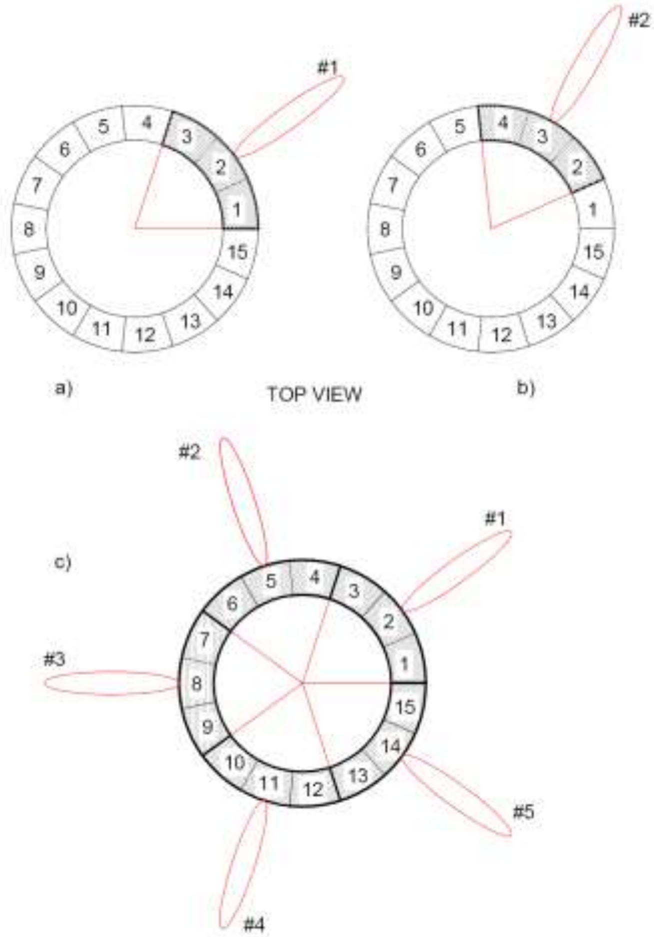

Figure 2. Antenna sectors division: *a)* beam of the sub-array #1, columns: [1-2-3], *b)* beam of the sub-array #2, colummns: [2-3-4], sub-array #1 and #2 are overlapped and they can not transmit simultaneously (they have common columns: [2, 3]); c) antenna sectors division for search function, sub-arrays #1, #2, #3 #4 and #5 are not-overlapping, and can transmit/receive simultaneously

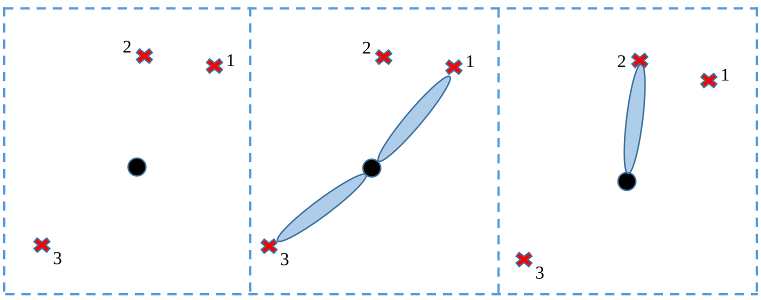

Figure 3. Parallel and consecutive tasks execution of the tracking function

III. Radar tasks scheduling

The goal of the scheduling algorithm is to allocate in a given time frame all the radar tasks with the correct update intervals, maximizing the tasks execution in parallel. The number of sectors, *M*, in which the antenna is divided defines the maximum number of parallel tasks executable, with some hypothesis and definitions being assumed in the following. We define the *task* as the basic radar activity composed by the transmission and reception of a waveform in a given direction. Each task belongs to a specific radar function (i.e. close range search, long-range search, tracking, detection confirmation etc.) and has its own dwell time, including the necessary transmission-wait-reception interval that depend on the distance of the target. In this paper, for the sake of simplicity, a dwell-time is intended to contain all the group of *n* pulses transmitted and received in the selected direction, *n* being defined according to the processing needs. The update interval is the time repetition of the task, depending on the requirements of the function to which the task belongs: typically for search purposes the update interval can be on the order of seconds (e.g. 2 to 6 seconds) while for the dedicated tracking it can be of the order of hundreds of milliseconds, (e.g. 100 ms) or less.

Tasks belonging to the same radar function have the same update interval. A radar function is exploited by several tasks: in surveillance, as many tasks as the number of pointing directions are necessary to cover all the search solid angle; while for the tracking functions the number of tasks is equal to the number of tracked targets; finally, the number of plots confirmation tasks depends on the number of detections to be confirmed. Then each task is defined by its dwell-time, *d*, its update interval, *u*, and by its pointing direction, θ and ϕ, (azimuth and elevation). As described in the previous paragraph, an azimuth direction is achieved using a particular subset of the antenna columns, called sub-array, and the elevation is obtained with the proper phase-shift between the columns elements. So we replace the pointing direction with an identifier, an integer number *s*, that recognizes univocally the sub-array needed for transmission and reception in the desired θ direction (no info about elevation is added since it has no influence on the following). We can image that at any time a radar control computer generates a list of *tasks* to be executed, and the scheduler attempts to deliver the optimal timeline solution. If the attempt fails, some tasks must be shifted in time (increasing or decreasing the update interval) or the search dwell time must be reduced (the consequence is a range reduction). Then a prioritization ordering is necessary to know the tasks to which the adjustments (update interval and dwell time) can applied first. Moreover, a scenario evaluation is needed to choose the optimal number of antenna sectors (*M*).

The proposed method starts next to the prioritization and antenna-into-sectors division, so we can image to have a list of tasks with assigned priorities and all the parameters *(d, u, s, M)* known.

A. *Optimization model*

In the following we introduce a model for the parallel scheduling of the tasks with the hypothesis that the update intervals and the dwell-times can be modified to obtain a substantial planning.

Let *N* the number of tasks to be scheduled. Each i^{th} task is represented by the set (d_i, u_i, s_i). The time-frame has a length *T* defined as: $T=LCM\ \{u_i\}$ (where *LCM* denotes the least common multiple). In a time-frame the i^{th} task has to be repeated $R_n=T/u_i$ times. Let $\underline{t_i} = \left[t_i^{(1)}, t_i^{(2)}, \dots, t_i^{(R_i)}\right]$ the optimal starting times vector (an ideal output to the scheduler) for the repetitions of the i^{th} task in the time-frame with the correct update interval. In a real operation, schedule results in a reduction and a time shift of the activities with respect to the ideal set $\underline{t_i}$, $i=1,2,..N$. Therefore, two *jitter* vectors are defined as follows: $\underline{c_i} = \left[c_i^{(1)}, c_i^{(2)}, \dots, c_i^{(R_i)}\right]$ $i=1, \dots, N$, contains the dwell times reductions and $\underline{j_i} = \left[j_i^{(1)}, j_i^{(2)}, \dots, j_i^{(R_i)}\right]$ $i=1, \dots, N$, with the update interval adjustment values, both referred to the i^{th} task. The output to the scheduling are the jittered starting times of the tasks: $\underline{t_i}' = \left[t_i^{(1)} + j_i^{(1)}, t_i^{(2)} + j_i^{(2)}, \dots, t_i^{(R_i)} + j_i^{(R_i)}\right]$, $i=1,\dots, N$, and the vector with the value of the dwell-times reductions for each tasks : $\underline{c_i}' = \left[c_i^{(1)}, c_i^{(2)}, \dots, c_i^{(R_i)}\right]$, $i=1, \dots, N$. The aim is to schedule as many tasks as possible with a minimum time-shift and a minimum dwell-time reduction. Hence, the objective function is the following:

$$F = \sum_{i=1}^{N} \sum_{k=1}^{R_i} \left(j_i^{(k)} + \left|c_i^{(k)}\right|\right) b_i^{(k)},$$

where $b_i^{(k)}$ is a binary variable equal to 1 if the k^{th} repetition of the i^{th} task is scheduled, and equal to 0 otherwise. An optimal solution to the tasks scheduling is the following optimization problem:

$$arg\ \min_{\underline{j_i}\ \underline{c_i}} F \qquad \textit{subject to } \zeta:$$

Where ζ is defined as follows:

the time execution of all tasks has to be contained in the defined time-frame *T*, and the update interval and dwell-time adjustments are limited by maximum allowed values:

$$t_N^{(R_N)} \le T \qquad (1)$$

$$0 \le j_i^k \le max\_j_i\ \forall\, i, k \qquad (2)$$

$$\left|c_i^k\right| \le max\_c_i \qquad \forall\, i, k \qquad (3)$$

A task can only start after the complete execution of the previous one. Let $\underline{\tau}$ be the time-ordered vector of the starting times of the scheduled tasks (the vector $\underline{\tau}$ does not consider parallel tasks, e.g.: if two or more parallel tasks are scheduled at a given time *t*, it will appear only once in $\underline{\tau}$ vector), and let $\underline{\delta}$ the related dwell-time vector. It follows:

$$\tau(n) \ge \tau(n-1) + \delta(n-1) \qquad \forall\, n \qquad (4)$$

Parallel tasks will have the same value of starting time, but the use of non-overlapping sub-arrays is necessary, so let us define:

$$\Delta t_{n,m}^{i,k} = \begin{cases} 0 & if\ t_n^{(i)} = t_m^{(k)} \\ 1 & otherwise \end{cases}, \forall\, n, m, i, k,$$

$\Delta t_{n,m}^{i,k}$ is equal to zero if the i^{th} repetition of the n^{th} task and the k^{th} repetition of the m^{th} task are simultaneous (i.e. they are parallel tasks). Finally let us define:

$$\Delta s_{n,m}^{i,k} = \begin{cases} 0 & otherwise \\ 1 \ if \ \|s_n - s_m\| < overlapping_{threshold} \end{cases}$$

$\forall \ n, m, i, k,$

$\Delta s_{n,m}^{i,k}$ is equal to one if the sub-array allocated to execute the i^{th} repetition of the n^{th} task and the sub-array allocated to execute the k^{th} repetition of the m^{th} task are overlapped. So to avoid the scheduling of parallel tasks executed by overlapping sub-arrays the following constrain is necessary:

$$\Delta t_{n,m}^{i,k} \leq \Delta s_{n,m}^{i,k} \ \ \forall \ m \neq n, i \neq k \qquad (5)$$

Finally, at any time the maximum number of parallel tasks must not exceed the number of antenna sectors, *M*:

$$\forall \ t_n^{(i)}, \ \sum \Delta t_{n,m}^{i,k} \leq M - 1, \ \ m \neq n \qquad (6)$$

The optimization model falls in the *mixed-integer problem* category, with a *NP-hard* solution and a great computational load. In the following, a heuristic solution is proposed based on an iterative time allocation method.

B. *Heuristic method*

An efficient heuristic method is proposed here in order to obtain a solution to the scheduling problem with the hypothesis that the radar control computer provides a list of tasks each one with its own priority and its optimal number of antenna sectors *M* derived from the evaluation of the scenario. The following assumptions is added: the priority order between the radar functions is known *a priori*. As an example: if at a certain time the active radar functions are long-range search, tracking and detections confirmation, the inter-functions priority is: *1)* tracking, *2)* detections confirmation, *3)* long-range search. Therefore, a final prioritized queue contain all the tasks order as inter-function and intra-function priority list. It is necessary to set the time sequence on which the tasks are allocated and to decide to which tasks the update interval and the dwell time adjustments are first applicable. The iterative method starts to allocate the tasks belonging to the function with the higher priority level. It starts allocating the repetition of the first priority task, allowing simultaneous execution of other suitable tasks. The suitable tasks for the parallel execution are those with non-overlapping sub-arrays, and equal dwell-time. This operation is iterated with all the tasks of the first function. Once all the tasks are allocated, the same method is applied with the tasks of the next, lower priority radar function. If at any time one or more repetitions of a task are not allocable due to an overlapping with another task, the algorithm attempts to adjust the interval update by shifting forward or backward the starting time. If a task is still not allocable the algorithm attempts to reduce its dwell time, otherwise the task is dropped. The update interval and the dwell time adjustments are limited to comply with pertaining maximum allowed values. By a proper setting of these values one can obtain a fixed, safe time scheduling for a certain function. As an example if dedicated tracking need strict time constraint, its maximum adjustments values will be set equal to zero, and its function priority level will be the highest, with the consequence that the time resources will be balanced by a range reduction of the surveillance function. In the following scheme the steps of the method are shown.

Algorithm:

```
for f =1 to F (priority ordered radar functions)
    for task=1 to n_F (i^th task of function f )
        allocate the task repetitions
        allocate suitable parallel tasks
        if allocation is not possible
            attempt to adjust update interval
            if update interval is not enough
                attempt to reduce dwell-time
                if allocation is not possible
                    drop task
                end if
            end if
        end if
    end for
end for
```

In the following paragraph a test of the method with different scenario is exposed, varying the number of targets (i.e. the number of dedicated tracking tasks to be scheduled) with a given set of active radar functions and related properties.

IV. Evaluation of test results

The performance of the method have been evaluated versus the scenario load, determining the maximum load that saturates the resources. The following hypothesis are assumed for the trials: *i)* parallel tasks are allowed only if they belong to the same radar function and have same dwell-times, *ii)* parallel tasks can be exploited using only equal-characteristics and non-overlapping sub-arrays.

The trials were developed considering a set of active radar functions with the relative parameters as shown in table 1. Some assumptions have been made on the radar system on which the scheduling algorithm is tested. The antenna can be divided into a number of sectors *M* from 5 to 30, the radar is able to perform long-range search up to a range of 100 km with an update-time of 6 s and with dwell-times equal to 10 or 20 ms (depending on the elevation direction). The radar performs dedicated tracking tasks with a range up to 40 km, with a dwell-time equal to 10 ms and a revisit time of 100 ms. The new surveillance detections must be confirmed with three consecutives illuminations that need 30 ms. The greater is *M*, the greater is the number of parallel tasks executable. However, the greater is *M* the lower is the sector transmitted power and antenna gain, due to the lower number of transmitting elements per sector, determining a loss factor. To recover this loss a greater dwell-time is needed. This has not consequences on the execution time of the surveillance function (the time saved by M increasing is balanced by the dwell-time increase). In the tracking function, increasing *M* does not imply a dwell-time increase since the tracking range is limited to 40 km. For this reason it has been assumed that the tracking function dwell time is equal to 10 ms. The number of 'looks' to cover all the search solid angle is 950 (780 at low elevation 0-20 degrees and 170 at high elevation 20-70 degrees), with *M=5* the dwell-time is 20 ms in low elevation (0-20 degrees) directions and 10 ms in high elevation (20-70 degrees) directions. Then, the time needed to execute the search in all solid angle is:

$$t_S = \frac{780}{M} t_d + \frac{170}{M} t_d = \frac{780}{5} 20 + \frac{170}{5} 10 = 3.46 \ s$$

as explained above t_S does not change varying M, if M increases, t_d increases).

TABLE I. PARAMETERS OF ENABLED RADAR FUNCTION FOR TEST

radar functions	solid-angle [°]	Range [km]	up-date interval [s]	dwell time [ms]	n. of tasks
Long-range search	360° 0-70°	0-100	6	10-20 **	***
Tracking	360° 0-70°	0-40	1	10	****
Plot confirmation	360° 0-70°	90-100	*	30	*****

* plot confirmation is considered as limited to only three consecutive tasks; ** variable with the elevation; *** defined to cover all the solid angel; **** variable from 10 to 100 with steps of 10; ***** variable from 10 to 50 with steps of 1

The trials was implemented by running the scheduling method with the tasks generated by the simulation of the spatial distribution of tracked targets and plots confirmation. The percentage of scheduled tasks, the free time resources and the maximum range reduction of the search function have been evaluated with varying M (from 5 to 30) and the number of tasks accordingly to table 1. For each combination between M and the number of tracked targets, several runs of the simulation were performed and the results were averaged. Figure 4 shows the mean percentage of dropped tracking tasks versus the number of targets to be tracked and versus the number of antenna sectors (M). The percentage values are color-coded by black (0%) to white (50%) as shown in the legend. As shown in figure 4, from 10 to 30 targets, for any value of M, all (100%) the tracking tasks are scheduled; from 40 to 70 targets the tracking performance shows a graceful degradation with no difference versus the number of antenna sectors. From 80 to 100 targets, it appears that if M is between 5 and 8 the percentage of dropped tracking tasks increase up to 50%, while if M is equal to 9 (or larger), the performance are quite similar and the percentage of dropped tracking tasks is no more 15%. Figure 5 shows the percentage of dropped search tasks after the scheduling of the tracking tasks, versus the number of tracked targets and versus the number of antenna sectors. From figure 5 it appears that only if the number of tracked targets is 10 it is possible to schedule all the search tasks to cover the required solid angle. When the number of tracked targets increases from 20 up to 40 the scheduled search tasks decrease to 15 %, when the targets are more than 50 it is not possible to allocate any search tasks, except a few number (about 15%) using M greater than 25. The performance are quite constant versus M. Figure 6 shows the percentage of the not-used time frame downstream the scheduling process. When the number of tracked targets is 10 the scheduled tasks need about the 80% of the total time-frame (that is 6 s), when the number of tracked targets is between 20 and 40 the time-frame utilization is more than 90% and goes up to 100% when the number of targets is more than 50. Let consider the case when the number of tracked targets is 20: all the tracking tasks are scheduled, not all the search tasks have been scheduled (55-90 %, depending on M) and not all the time-frame has been used, still about 10% is available. The last two results look like a contradiction, but the reason is the fragmentation of the time-frame due to the high repetition frequency of the tracking tasks, with the consequence that the available time-slots are not long enough to contain a search dwell-time.

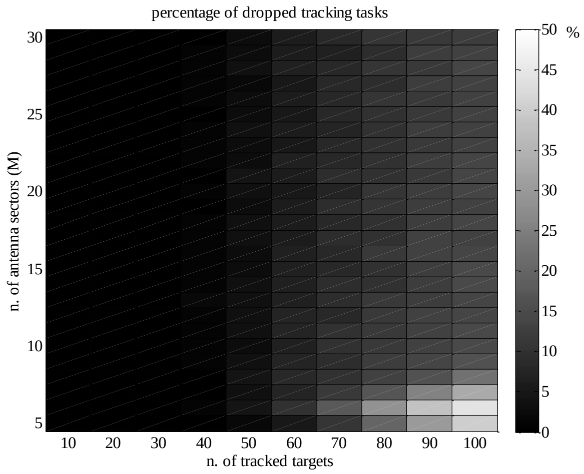

Figure 4. Percentage of dropped tracking tasks versus the number of tracked targets and the number of antenna sector (M)

It has been observed an increase of the percentage of allocated search tasks if the search range is reduced from 100 km to 50 km. The results are essentially the same as in figure 5, adding +10 to the values on the x-axis. To evaluate the scheduling algorithm behavior versus the number of antenna sectors the results has been aggregated and weighted by a cost-function defined as:

$$f_i = \frac{2*P_S+P_{ft}-4\,P_{tr}}{\|2*P_S+P_{ft}-4\,P_{tr}\|}, \quad with\ i = 5, 6, \ldots, 30,$$

where P_S is the percentage of scheduled search tasks which weight is 2, P is the percentage of utilized time-frame and P_{tr} is the percentage of dropped tracking tasks with a higher weight equal to 4. Figure 7 shows the values of the cost function: the score increases as M increases with not much difference when M is greater than 8.

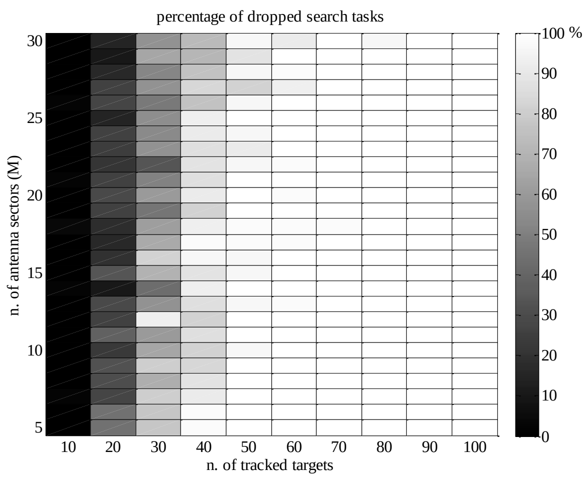

Figure 5. Percentage of dropped search tasks versus the number of tracked targets and the number of antenna sector (M)

The test demonstrates that for the considered radar system and its related functions, the dedicated tracking and search tasks can be scheduled, with some losses as the number of targets increases, and that is preferable to use M equal or greater than 8.

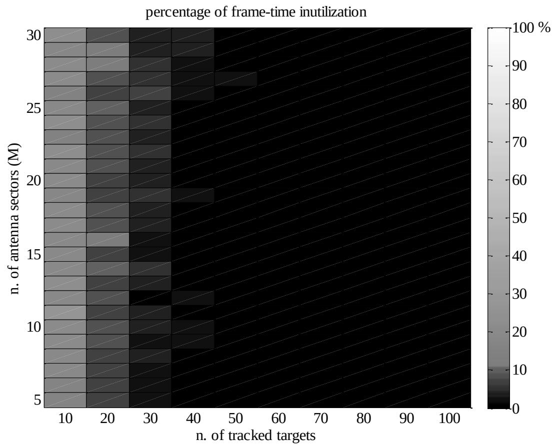

Figure 6. Percentage of not-used time-frame versus the number of tracked targets and the number of antenna sector (*M*)

Moreover even if tracking or search tasks were dropped a moderate waste time occurs, as it can be evaluated comparing figures 4, 5 and 6. The waste time is computed as the smallest between the not utilized time and the time need to complete the dropped tasks. The results with respect to the time-frame length (6 s) is less 10 % when targets are 20, less than 5% when the targets are 30 and very poor for other values, as shown in figure 8, where the results, averaged on the number of sectors, are shown versus the number of tracked targets.

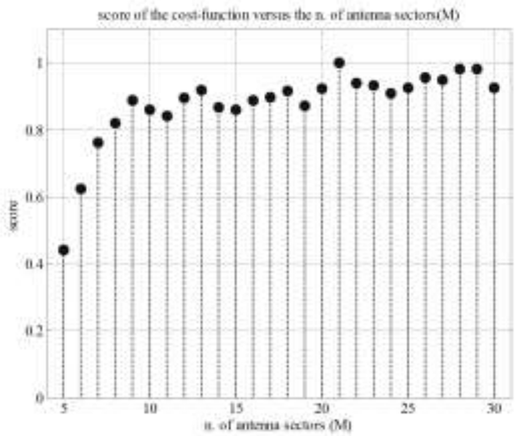

Figure 7. Score of the results cost-function versus the number of antenna sector (*M*)

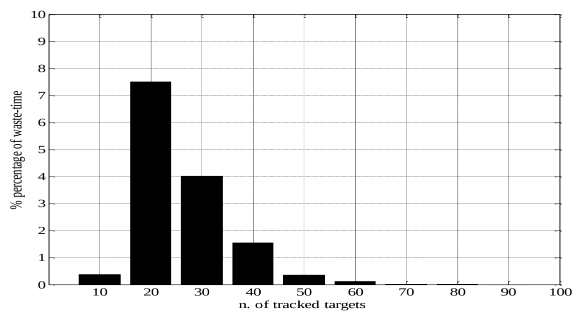

Figure 8. Percentage of waste time versus n. of tracked targets

V. Conclusions

A method to schedule radar tasks for a conformal array multifunction radar has been presented. The trials show the feasibility of the method for a particular set of radar functions with encouraging results about the balance between the waste time and the dropped tasks. For the study case the dedicated tracking function has the highest priority, then as the number of tracked targets increases the available time for search decreases. However, the vice-versa can be obtained (to prefer the search function with time taken from tracking function) just defining a different inter-functions priority. The trials were performed using all values of the number of antenna sectors, but the method should be completed with an algorithm capable to look for the optimal value of *M* as function of the 'scenario'.

Further possible developments are the study of the feasibility and of eventual benefits of: *i)* the possibility to define simultaneous antenna sectors with different number of columns (for range adaptation); *ii)* the possibility of varying M into a single time-frame; *iii)* the possibility to schedule parallel tasks belonging to different radar functions; iv) the possibility of a vertical partitioning of the sectors (for dealing with targets with the same azimuth but different height). Moreover, future study can concern the behavior of the radar when a simultaneous azimuthal coverage is done by an high number of the antenna sectors (ubiquitous radar), analyzing the benefits and the related optimal resources management and scheduling.

References

[1] Dale R. Billetter, Multifunction Array Radar, Artech Hous 1989

[2] S. Sabatini, M. Tarantino, "Multifunction Array Radar – System design and analysis", Artech Hous 1994.

[3] S.L.C. Miranda, C.J. Baker, K. Woodbridge, H.D. Griffiths "Comparison of scheduling algorithms for multifunction radar" IET Radar Sonar Navig., 2007, 1, (6), pp. 414-424.

[4] A. Orman, C. Potts, A. Shanani, A. Moore "Scheduling for a multifunction phased array radar system" Eur. J. Operations Res., pp. 13-25, Apr. 1996.

[5] J. Butler "Multi-function radar tracking and control" Ph.D. dissertation, UCL Univ. London, UK, 1998.

[6] D. Stromberg, P. Grahn "Scheduling of tasks in phased array radar", in Proc. IEEE Int. Symp. Phased array Syst. Tech., Oct. 1996, pp.318-321.

[7] E. Winter, P. Baptiste "On scheduling a multifunction radar", Aerospace Science and Technology, 11, 2007, pp. 289-294.

[8] H. Mir, J.D. Wilkinson "Task scheduling algorithm for an air and missile defense radar", in Proc. of IEEE Radar Conf., 26-30 May 2008, pp. 1-6.

[9] T-W. Kuo, Y-S. Chao, C-F. Kuo, C. Chang, "Real-time dwell scheduling of component-oriented phased array radars", IEEE Trans. on Computers, vol. 54, n. 1, January 2005, pp. 47-60.

[10] V. Jeauneau, T. Guenais, F. Barbaresco, "Scheduling on a fixed multifunction radar antenna with hard time constraint", in Proc. of Radar Symposium IRS 2013, 19-21 June 2013, pp. 375-380.

[11] H. Mir, F.B. Abdelaziz, "Cyclic task scheduling for multifunction radar", IEEE Trans. on Automation Science and Engineering, vol. 9, n. 3, July 2012, pp. 529-537.

[12] H. Mir, A. Guitouni, "Variable dwell time task scheduling for multifunction radar", IEEE Trans. on Automation Science and Engineering, vol. 11, n. 2, April 2014, pp. 463-472.

[13] Fincantieri S.p.A. "Radar bistatico (bistatic radar)", patent application n. RM2014A000005, 9 jan. 2014.

[14] G. Galati, F. Madia, P. Carta, E.G. Piracci, R.Stallone, M. Massardo, "Time for a change in phased array radar architectures - Part I: Planar vs. Conformal array" in Proc. of IRS Jun 24-26, 2015, Dresden, Germany.

[15] G. Galati, F. Madia, P. Carta, E.G. Piracci, S. Franco, S. Quattrociocchi, "Time for a change in phased array radar architectures - Part II: the d-Radar" in Proc. of IRS 2015 June 24-26, 2015, Dresden, Germany.