Adaptive Scheduling Algorithm for ISAR Imaging Radar Based on Pulse Interleaving

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Abstract. Aiming at imaging task scheduling of multifunction phased array radar, this paper puts forward an adaptive scheduling algorithm for ISAR imaging radar based on pulse interleaving. Firstly, required resources for sparse aperture ISAR imaging were calculated according to initial cognition of target feature, based on that, a rational and optimized scheduling model of interleaving pulse dwelling is established, then radar resources can be allocated reasonably under the dual restraints of time and energy. At last, different targets were imaged respectively using compressed sensing-based sparse aperture ISAR imaging method and required imaging resolution is achieved while resource utilization rate is enhanced apparently. The simulation testified the feasibility of this algorithm.

Keywords: Phased array radar · Resource scheduling · Pulse interleaving Sparse aperture imaging

1 Introduction

Recently, phased array radar (PAR) has been widely used. Compared with the conventional mechanical scanning radar, PAR has microsecond beam agile ability and controllable spatial resource allocation capability [1]. Reasonable, flexible and efficient scheduling strategy is the key to its advantage [2].

Scheduling method of phased array radar can be divided into two categories: template-based scheduling and adaptive scheduling. The adaptive scheduling method according to the environment and tasks adjust the resource scheduling strategy flexibly, which is the most effective, but also the most complex scheduling method [3]. In [4–7], a variety of adaptive scheduling algorithms are proposed for different radar tasks, such as target search and tracking. However, the resources of the system are not fully exploited. Pulse interleaving technology can improve the resource utilization of the radar system; its core idea is to schedule the transmitting or receiving pulse of other tasks in a single task pulse interval. Aiming at the time allocation of the PAR and

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MIMO radar, some scheduling algorithm are proposed, which improves the time efficiency and energy utilization efficiency. A scheduling algorithm for digital array radar is proposed to solve the problem of dwell scheduling in [10]. The resource utilization of the traditional radar resource scheduling algorithm is optimized by using the pulse interleaving technique in [11–13]. However, most of the proposed algorithms only deal with the task of search and tracking, but don't take the imaging task into account. In fact, target imaging can provide important support information for target classification and recognition, and it is one of the important functions of PAR. Due to the imaging function need continuous time resources, so the resource utilization is low.

Under the framework of CS theory, continuous observation of the target image can be transformed into random sparse imaging, and in the sparse aperture condition, high-quality target ISAR image can be obtained [14]. This provides an effective technical support for incorporating imaging task requirements into the phased array radar resource scheduling model. Aiming at the imaging tasks, a resource scheduling algorithm is proposed in [15], but the algorithm only schedules from the beam, and does not utilize the time resource of the dwell waiting period.

Based on the above issues, a scheduling algorithm for ISAR imaging radar based on pulse interleaving is proposed in this paper, which can further improve the utilization ratio of radar resources.

2 Background

In this section, some background including the cognitive feature of target and the sparse aperture ISAR imaging are briefly reviewed.

2.1 The Cognitive Feature of Target

It is necessary to calculate the radar resources need for ISAR imaging tasks based on the results of target features to establish a reasonable pulse interleaved resource scheduling model. Sparse aperture ISAR imaging based on CS theory has made great achievements in recent years. In order to improve the adaptive ability of the radar imaging, the method in [15] can be used to recognize the characteristics of the target after entering the stable tracking phase. With the cognitive results of target features, the demand of radar resources for target imaging can be calculated. Using conventional tracking algorithms, the distance $\hat{R}$, speed $\hat{V}$, heading of the target $\hat{\theta}$ can be obtained; the target size $\hat{S}$ can be estimated; the azimuth sparsity $\hat{K}$ is defined as the number of distance units of azimuth direction is larger than the set threshold for each direction of the target rough resolution ISAR image; the observation time $\hat{T}_c$ is calculated from the reference azimuth resolution required for the reference target imaging; the relative priority P is calculated according to the distance, velocity and heading of the target.

2.2 Sparse Aperture ISAR Imaging

In the ISAR imaging process, the main position and amplitude information in the echo are mostly provided by strong scattering points while the weak scattering points contribute little to the echo. Therefore, using the recognition of target features, we can realize the sparse aperture cognitive ISAR imaging. Assume the accumulation time of the i-th target imaging is $\hat{T}_c$ after the feature recognition, $N = PRF \cdot \hat{T}_c$ pulses are transmitted, and the discretization of the full aperture is represented as $s_r(t, m)\ , m = 1, 2, \ldots, N$. There are $M(M < N)$ sub-pulses transmitted to the target, and the signal with sparse aperture is $s_r(t, m')\ , m' = 1, 2, \cdots, M$. For the i-th target, if the sparsity is $\hat{K}_i$, then the dimension M_i of azimuth observation after dimension reduction is expressed as:

$$M_i \geq c\hat{K}_i \ln(N_i) \tag{1}$$

Where c is a constant associated with the recovery accuracy. The Fourier transform matrix is selected as the sparse transformation matrix $\boldsymbol{\Psi}$ of signal $\boldsymbol{x}$. According to the sparse aperture distribution, the observation matrix $\boldsymbol{\Phi}$ can be designed as

$$\phi(m', m) = \begin{cases} 1, & \{(m', m) \mid m' = m\} \\ 0, & else \end{cases} \tag{2}$$

It has been proved in [16] that the observation matrix is not related to the sparse transform matrix. Reconstructing azimuth information by solving the optimization problem:

$$\boldsymbol{\Theta} = \min \left\| \boldsymbol{\Psi}\boldsymbol{\Phi}^H S_r(f, \tau_m) \right\|_1, \ s.t. S_r(f, \tau_m) = \boldsymbol{\Psi}\boldsymbol{\Phi}^H \boldsymbol{\Theta} \tag{3}$$

The azimuth imaging of each distance unit is carried out according to the above method, and the matrix form is the ISAR image of the target.

3 Resources Scheduling of Radar Imaging Task

According to the sparse aperture cognitive ISAR imaging method, this paper proposes an adaptive scheduling strategy based on pulse interleaving. The proposed algorithm can significantly improve the resource utilization rate as well as obtain satisfying target imaging resolution.

3.1 Pulse Interleaving

The pulse dwell of the radar task is usually composed of the transmitting period, the waiting period and the receiving period. The radar can't be preempted in the process of transmitting and receiving pulses, but in the waiting period, the antenna is idle. Therefore, it is possible to take full advantage of the time resources of the waiting period for transmitting or receiving other tasks. This is the essence of pulse interleaving technique. By optimizing the beam level to the pulse level, the advantages of phased array radar beam agility can be further improved, as well as the utilization rate.

Pulse interleaving can be divided into the cross interleaving and the internal interleaving, which is shown in Fig. 1.

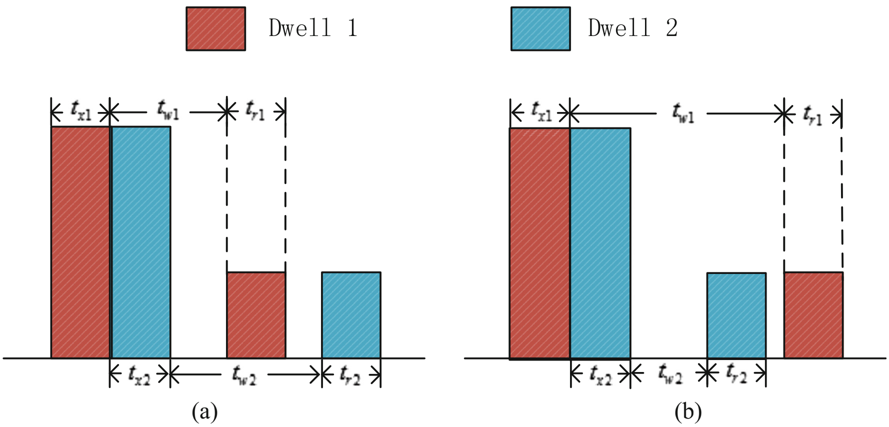

Fig. 1. Two forms of pulse interleaving. (a) The cross pulse interleaving, (b) the internal pulse interleaving.

Where t_{xj}, t_{wj}, t_{rj} denote the transmitting period, waiting period and receiving period of dwell $j(j = 1, 2)$ respectively. The time constraints of the two interleaving modes can be expressed as:

$$t_{w1} \geq t_{x2},\ t_{w2} \geq t_{r1},\ t_{x2} + t_{w2} \geq t_{x1} + t_{r1} \tag{4}$$

$$t_{w1} \geq t_{x2} + t_{w2} + t_{r2} \tag{5}$$

In the actual scheduling process, the number of the pulse interleaving is restricted by the energy constraint condition, so as to avoid the long working time of the transmitter. The energy constraint of radar system is divided into steady state energy constraint and transient energy constraint. Since the total energy consumption threshold of the steady-state energy constraint is constrained by the performance of the device, only transient energy constraint is usually considered. The transient energy at t moment can be defined as:

$$E(t) = \int_0^t P(x)e^{(x-t)/\tau}dx \tag{6}$$

Where, $P(x)$ denotes the power parameter and τ denotes the back-off parameter which is related to the heat dissipation of the system.

In the process of pulse interleaving, the energy constraint can be defined as $E(t)$, which cannot exceed the maximum threshold $E_{\max}$ of instantaneous energy at any time, i.e.

$$E(t) \leq E_{\max} \tag{7}$$

In simulation, the energy consumption of radar beam and the variation of energy state in time Δt can be prior estimated by the parameters of antenna gain, transmission power, and pulse width and pulse number, so as to reduce the complexity of algorithm.

3.2 Resource Scheduling Algorithm for Radar Imaging Tasks

This paper presents an adaptive scheduling algorithm for radar imaging resources based on pulse interleaving. Firstly, the method in [10] is used to recognize the characteristics of the target, and then calculate the observation time $\hat{T}_{ci}$, azimuth observation dimension $\hat{M}_i$ and relative priority P_{ki} of each target imaging. On this basis, the pulse interleaving technology is used to allocate the radar resources from the high to the low. The waiting period t_{wi} of the mission dwell can be calculated from the distance between the radar and the targets which is obtained from the cognitive. The schematic of ISAR task scheduling based on pulse interleaving is shown in Fig. 2.

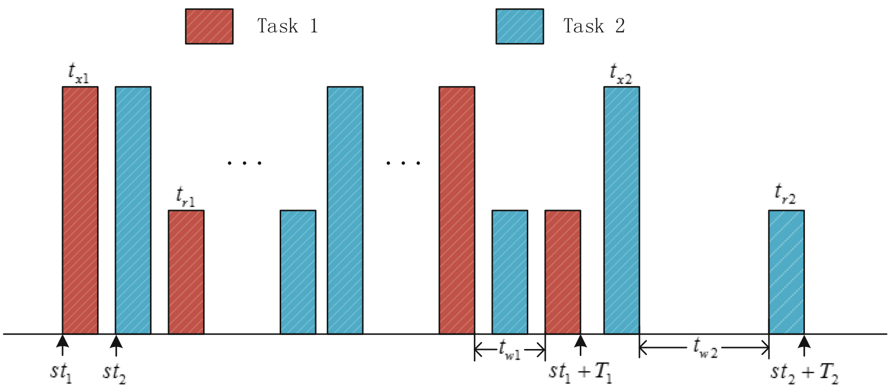

Fig. 2. The schematic of ISAR task scheduling based on pulse interleaving.

The scheduling success ratio (SSR), the hit value ratio (HVR), the time utilization ratio (TUR) and the energy utilization rate (EUR) are taken as the criterion.

(1) The scheduling success ratio (SSR): The number of imaging tasks performed to the actual number of imaging task. It can be expressed as:

$$\mathrm{SSR} = \frac{N'}{N} \tag{8}$$

(2) The time utilization ratio (TUR): The ratio of the total dwell time to the total scheduling time. It can be expressed as:

$$\mathrm{TUR} = \frac{\sum_{i=1}^{N'} (t_{xi} + t_{ri}) \cdot M_i}{T_{\mathrm{total}}} \tag{9}$$

(3) The energy utilization rate (EUR): The ratio of the energy consumed by all the transmit pulses to the total energy supplied by the system. It can be expressed as:

$$\text{EUR} = \frac{P_t \cdot \sum_{i=1}^{N'} (t_{xi} \cdot M_i)}{P_{av} \cdot T_{\text{total}}} \tag{10}$$

Where N denotes the total number of tasks for request scheduling, N' denotes the successfully scheduled numbers, t_{xi} and t_{ri} denote the transmission time and the reception time of the pulse in the i-th task respectively; M_i is the dimension of azimuth observation; T_{total} is total simulation time, P_t is the peak power of each transmitted pulse and P_{av} is the average power delivered by the radar. So the radar imaging task model can be established as:

$$\max\{q_1 \frac{N'}{N} + q_2 \sum_{i=1}^{N'} \frac{\sum_{i=1}^{N'} (t_{xi} + t_{ri}) \cdot M_i}{T_{\text{total}}} + q_3 \frac{P_t \cdot \sum_{i=1}^{N'} (t_{xi} \cdot M_i)}{P_{av} \cdot T_{\text{total}}}\}$$
$$s.t. \begin{cases} \max(t_0, et_i) \le st_i \le \min(et_i + \omega_i, t_{end}), i = 1, 2, \cdots N' \\ \cap_{i=1}^{N'} [st_i,\ st_i + t_{wi}] \cup [st_i + t_{xi} + t_{wi},\ st_i + t_{xi} + t_{wi} + t_{ri}] = \emptyset \\ \boldsymbol{T}[st_i : st_i + t_{xi}] = \boldsymbol{T}[st_i + T_{ci} - t_{ri} - t_{wi} - t_{xi} : st_i + T_{ci} - t_{ri} - t_{wi}] = a_i \\ \boldsymbol{T}[st_i + t_{xi} + t_{wi} : st_i + t_{xi} + t_{wi} + t_{ri}] = \boldsymbol{T}[st_i + T_{ci} - t_{ri} : st_i + T_{ci}] = -a_i \\ \text{Insert } M_i - 2 \text{ transmitting and receiving pulses in } (st_i, st_i + T_{ci}) \\ E(t) \le E_{\max},\ t \in [t_0, t_{end}] \end{cases} \tag{11}$$

Where et_i denotes the expected start time; st_i denotes the actual start time of the task scheduling; T_{ci} denotes the azimuth coherent accumulation time; ω_i denotes the time window of the i-th task; The vector $\boldsymbol{T}$ denotes the dispatching state of the discretized time interval; a_i is the task number of the i-th task; q_1, q_2, q_3 is the adjustment coefficient. The first and second constraints represent the time constraints that the task scheduling needs to satisfy; the third to fifth constraints represent the sparse aperture conditions and the observation time range that the imaging task needs to satisfy; the sixth constraint represent the energy constraints that the task scheduling needs to satisfy.

Discretize the system time, and the length of each time slot is Δt. Assuming that the target is to be imaged in the scheduling interval $[t_0, t_{end}]$, and the resource scheduling algorithm for ISAR imaging radar is described as follows:

Step 1: Sending a bit of pulse to recognize target features, and calculate the azimuth coherent accumulation time and the observation dimension according to the echo feedback information.

Step 2: Add the task of the latest scheduled start time less than t_0 and the task that the sum of the earliest scheduling start time and the azimuthal coherent accumulation time is greater than t_{end} to the delete list, According to the priority, join the remaining $N - K$ tasks to the application list (tasks with the same priority are arranged according to the expected execution time), and let $i = 1$.

Step 3: Let that t_{p_first} points to the first transmit pulse of the i-th imaging task, i.e. the expected start time of the task scheduling and t_{p_end} points to the last transmit pulse, so $t_{p\_end} = t_{p\_first} + T_{ci} - t_{w_i}$.

Step 4: If t_{p_first} and t_{p_end} determine the end of the transmission pulse to the interval, and $M_i - 2$ pulse pair is succeed inserted under the constraint of time and energy, then dispatch the imaging task in this manner and update the energy state of each time slot, $i = i + 1$, turn to step 5. Otherwise let $t_{p\_first} = t_{p\_first} + \Delta t_p$ and $t_{p\_end} = t_{p\_end} + \Delta t_p$($\Delta t_p$ denotes the minimum step size). If $t_p < st_i + \omega_i$, return to step 4, otherwise the task cannot be scheduled and added to the delete list, let $i = i + 1$, and return to step 3.

Step 5: If $i \leq N - K$, return to step 3, otherwise, if $i > N - K$, return to step 6.

Step 6: Using the sparse aperture imaging method, the ISAR image can be obtained. Then end the schedule.

The flame of ISAR task resource scheduling is shown in Fig. 3.

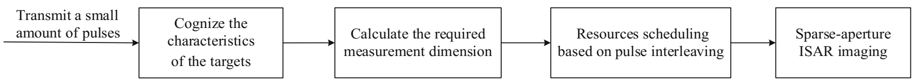

Fig. 3. The flame of ISAR task resource scheduling.

4 Simulation Experiments

In the simulation, suppose the radar transmits LFM signals, in order to get more accurate simulation results, set both the transmit pulse width and the minimum pointer sliding step to 10 μs, the time window is 1 ms, the simulation time is 1 s, the pulse power is 4 kW, and the average power is 500 W. The distance between the target and the radar is 0 to 30 km.

It should be noted that the arrival time of radar echo is affected by the dimension of the target in rang direction. In order to ensure the imaging quality, the received pulse should be broadened properly. Suppose that the distance from the radar to the i-th target is R_i and the dimension of the target in rang direction is $\hat{S}_{y_i}$, the width of the actual received pulse of the i-th imaging task can be expressed as:

$$t'_{wi} = \frac{2(R_i + \hat{S}_{y_i})}{c} \tag{12}$$

Compare the traditional radar imaging task scheduling algorithm (traditional algorithm) in [15] and the radar imaging task scheduling algorithm proposed in this paper (proposed algorithm). In order to effectively receive echoes of all imaging targets, the dwell waiting period in the conventional algorithm is set as the round trip time between the radar and the farthest target. The results of the comparison are shown in Fig. 4.

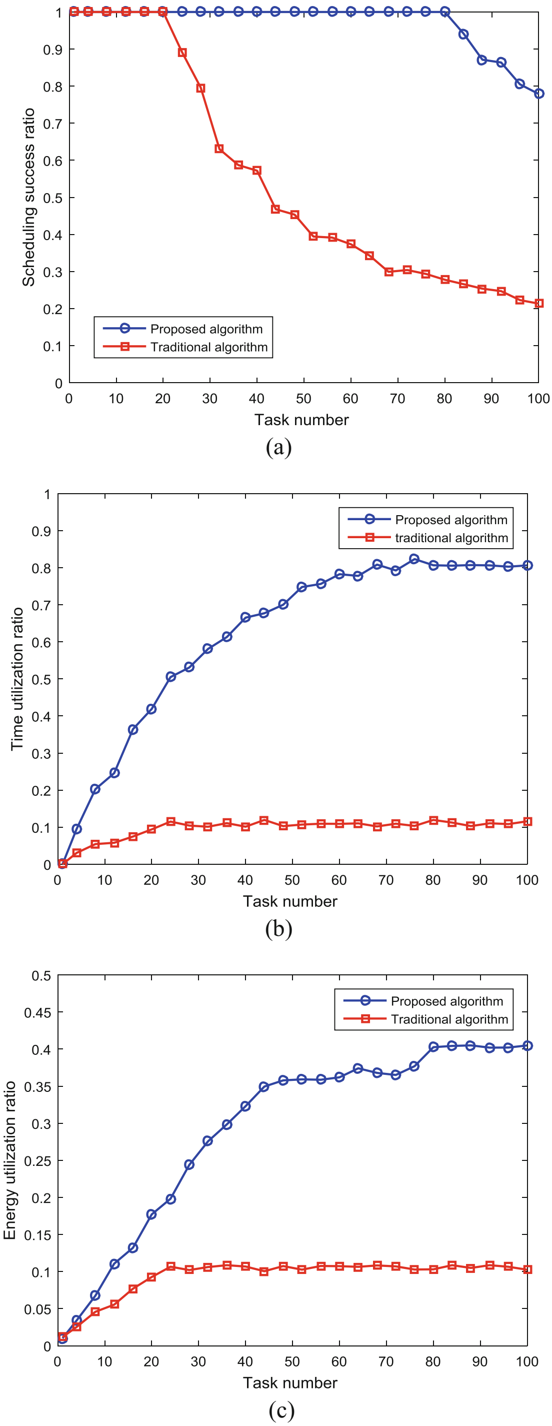

Fig. 4. The comparison of two scheduling algorithms. (a) The scheduling success ratio, (b) the time utilization ratio, (c) The energy utilization ratio.

From Fig. 4(a) we can see that when the number of tasks is small, both algorithms can successfully schedule all the imaging tasks, and the scheduling success rate is 100%. When the number of tasks is more than six, the scheduling success rate of the traditional algorithm begins to decline significantly, but the proposed algorithm can still successfully schedule all tasks until the task number reaches to 80. This is because the proposed algorithm takes full advantage of the idle time of the task pulse to schedule other tasks, which can take full advantage of the system time resources.

From Fig. 4(b) and (c), we can see that the proposed algorithm takes full advantage of the time resources of the pulse waiting period, and the number of tasks successfully scheduled in the same scheduling time is large, which makes the time utilization ratio and energy utilization ratio can reaches to 80% and 40%, and after the number of imaging tasks is more than 6, both the time utilization ratio and energy utilization ratio are far higher than the traditional algorithm.

5 Conclusion

In this paper, a scheduling algorithm for ISAR imaging radar based on pulse interleaving is proposed. The resource scheduling model for pulse interleaving is established and the realization method of online pulse interleaving under the constraint of time and energy resources is designed. Theoretical analysis and simulation results show that: the proposed algorithm can greatly improve the success rate and resource utilization of the system by reasonably utilizing the resource of the pulse waiting period.

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