Interleaving Scheduling Algorithm for SLM Transactions in Mode S Surveillance Radar

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Abstract. Mode S Secondary Surveillance Radar establishes selective and univocally addressed transactions with aircraft within its coverage while using efficiently the available budgets of time and energy. This benefits are key to supporting high-traffic density. A preliminary interleaving algorithm for the scheduling of Short Length Message transactions is presented and tested under a heavy load simulated scenario.

1 Mode S SSR and Resource Management

Mode S (Selective) is a Secondary Surveillance Radar (SSR) process that allows selective interrogation of aircraft according to the unique 24-bit address assigned to each aircraft. Such selective interrogation improves the quality and integrity of the detection, identification and altitude reporting with the addition of new reports from the aircraft and data-link capabilities. These improvements translate into benefits in terms of safety, capacity and efficiency, benefits which are key to supporting high-traffic density scenarios [1] [2].

The radar resource management function plays a critical role to maximize the radar resource usage for improving performance. In addition to the tracking tasks, the system also includes search and target confirmation tasks. A search task involves looking for new targets in the sky and a target confirmation task confirms the target after it is detected by the search task. Due to the multidimensional nature of radar resource allocation, the problem of optimally determining the process of resource allocations to maximize total system utility is NP-hard [3].

The radar resource management function includes a specific scheduling algorithm for the several transactions of the tracking task [4] [5]. The scheduling algorithm considers waveform, beam shape, type of coding, dwell time, pulse repetition frequency, energy level, the time characteristics of the transactions and aircraft predicted positions. Since the targets move continually, and sometimes evasively, the resource allocation and scheduling decisions must be made frequently and in real-time.

Dwell time in a radar is the time that an antenna beam spends on a target. The beam dwell time of a 2D surveillance radar is derived from the antenna horizontal beam width and the turn speed of the antenna [6]. In Mode S SSR, during the beam dwell time, there is an alternation of two basic types of tasks, broadcasting and selective[3]. Broadcasting periods include Mode A/C searches and transactions (for compatibility with heritage radars and transponders), and Mode S searches. Selective periods include Mode S selective tracking transactions. Commonly, one-third of the beam dwell time is for broadcasting tasks.

Some characteristics of a Mode S SSR radar system of particular interest in resource management are [7] [8]:

– Each Mode S selective transaction is compose of three phases in sequence: a transmission phase, a waiting phase and a receiving phase.
– Once a transmission or a reception starts, it cannot be preempted.
– The waiting phase is a wasting of time for a transaction.
– Transactions overlapping in the same beam can be interleaved by scheduling the transmit and/or receive phase of one transaction in the wait phase of another transaction.
– The longer the distance between the target and the radar, the higher the energy requirement.

Due to the selective nature of the Mode S transactions, interleaving is mandatory for high-traffic density. The waiting time may change from one dwell to the next depending on the velocity vector of the aircraft relative to the radar. Therefore, the radar should be able to predict the approximate waiting time based on the previous tracking information about the aircraft.

The energy of the transmissions may be modulated by the distance, but this could result non-viable for some radar electronic implementations.

Section 2 shows the characteristics of Mode S transactions. Section 3 present an interleaving algorithm for SLM Mode S transactions. In Section 4 simulation results of the use of the algorithm are presented. Finally, section 5 draws some conclusions and sketches future work.

2 Mode S SSR Transactions

Figure 1 shows the phases of a transaction as part of a Mode S tracking task. The transmission interval is t_{X} while the reception period t_{r} begins after a waiting time t_{W}. The cool-down interval, t_{C}, precedes the transmission interval of any transaction [3]. During this interval, there is no transference, and therefore it contributes to the evacuation of the heat from the active components of the radar. In the algorithm presented here the cool-down is a non conditioned variable. The interval time t_{V} represents the remaining time to the next transactions programmed for the current aircraft task. Even when the next transaction is normally programmed for the next antenna azimuth scan in a rotating surveillance radar, current transaction could be repeated in the present beam dwell for particular reasons.

[3] In the literature [7] these types of periods are called SSR/all-call period and Mode S roll-call period, respectively.

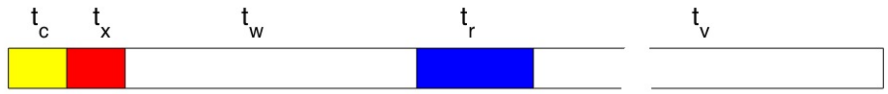

Fig. 1: Transaction Time Intervals.

Transactions are characterized by the duration and coded features of the pairs transmission and response. From an scheduling point of view only the time intervals are relevant. Table 1 shows the possible pair combination encountered for Short Length Messages (SLM)[9].

#	Transaction	t_X	t_R
1	Surveillance/Surveillance	20μs	64μs
2	CommA/Surveillance	34μs	64μs
3	Surveillance/CommB	20μs	120μs
4	CommA/CommB	34μs	120μs

Table 1: SLM Transaction Types

3 Interleaving Algorithm for SLM Mode S

The phases t_X and t_R are non-preemptive, since a radar can only perform a single transmission or a single reception at a time. However, t_C of one task can be overlapped with t_R or t_W of another task, since the radar can cool down during the waiting and the receiving period. Allowing the entire duration of a transaction (from transmission start to reception end) to be a non-preemptive job wastes resources and decreases the schedulability of the system [3]. Transactions can be interleaved to improve schedulability. The constructed interleaving may not be optimal in some restricted sense [10] [11] [12], but it must be effective for the target application, and preferably simple and with well-known properties.

Transactions can be interleaved in two ways: (a) properly nested interleaving and (b) improperly nested interleaving. Two transactions are said to be properly nested if one transaction fits inside the waiting time (t_W) of another, as in the left transactions in Figure 2. Two transactions are said to be improperly nested when one transaction only partially overlaps with another as illustrated by the right transactions in Figure 2.

Suppose that transaction T1 is improperly interleaved with transaction T2, where T1 starts first. Transaction T1 is called the leading transaction and transaction T2 is called the trailing transaction. Based on the phasing illustrated

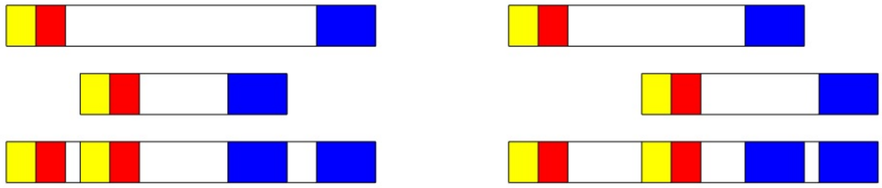

Fig. 2: Properly (left) and Improperly (right) Interleaving.

in Figure 2, the necessary conditions for the interleaving to occur are given by Equations (1) and (2),

$$t_{\mathrm{W1}} \geq t_{\mathrm{C2}} + t_{\mathrm{X2}}, \tag{1}$$

$$t_{\mathrm{C2}} + t_{\mathrm{X2}} + t_{\mathrm{W2}} \geq t_{\mathrm{W1}} + t_{\mathrm{r1}}. \tag{2}$$

A phase offset for a improper interleaving is defined in (3) [13]. The value of the phase offset determines how tightly two nested tasks fit together. The aim is to minimize this offset in reception because it is a useless wasting of time,

$$o_i = t_{\mathrm{C2}} + t_{\mathrm{X2}} + t_{\mathrm{W2}} - (t_{\mathrm{W1}} + t_{\mathrm{r1}}). \tag{3}$$

Cool-down time t_{C2} could have any positive value larger than a prescribed or derived minimun. For SLM $t_{\mathrm{r}} > t_{\mathrm{X}}$; if $t_{\mathrm{W1}} \geq t_{\mathrm{W2}}$ is taken, then o_i can be fixed to 0 and the following is derived,

$$t_{\mathrm{C2}} = (t_{\mathrm{W1}} - t_{\mathrm{W2}}) + (t_{\mathrm{r1}} - t_{\mathrm{X2}}) > 0, \tag{4}$$

$$t_{\mathrm{C2}} \geq \min(t_{\mathrm{C2}}) = t_{\mathrm{r1}} - t_{\mathrm{X2}} > 0. \tag{5}$$

It means that for SLM, when interleaving condition are satisfied, the algorithm can forces offset $o_i = 0$ because the value of t_{C2} remains > 0 for any other condition.

The implemented algorithm starts with the transaction of the largest waiting time t_{W1}, and attempts to interleave it, avoiding overlapping, with the transaction with the largest possible t_{W2} smaller than that of the leading transaction based on the stated conditions (1) and (2) with $o_i = 0$. Cool-down time t_{C2} is a non conditioned variable derived in the process.

The algorithm repeats the process[4] taken the actual trailing transaction as the next leading transaction until it reaches the transaction with the smallest t_{W} that can no longer be interleaved, or all transactions are interleaved to form a single virtual transaction called a cycle [7].

If there is a backlog of transactions, the process is repeated until all transactions are included in as many cycles as necessary.

[4] The conditions of equations (1) and (2) have to be suitably modified.

The improperly nested algorithm ensures that in any cycle the transmissions and receptions are equally sequenced. That is not the case for the properly nested alternative.

As was mentioned, for any type of SLM transaction t_{X} is shorter than t_{r}. As a consequence of that condition, it was demonstrated that the sequence of receptions of any cycle does not have gaps[5]. Meanwhile the sequence of transmissions of any cycle has transmission silences that contribute to cool down the active components of the radar[6].

4 Algorithm Test for Heavy Load Simulated Scenario

SLM are used in level 1 (CommA) and level 2 (CommB) data-link services in Mode-S SSR, particularly in the GICB (Ground Initiated CommB) protocol as used in the Mode S Enhanced Surveillance (EHS)[14].

Even when SLM includes different types of transaction, entirely GICB transactions are used for testing, as recomended by Eurocontrol; this corresponds to transaction #4 in Table 1. The distribution of aircraft in the high-traffic density scenario follows the non uniform histogram of Table 2 [15]. A uniform random distribution is applicable in each range band.

Range NM	5-10	10-20	20-40	40-60	60-80	80-90	90-130	130-150
Distribution	1	3	12	7	7	2	6	10

Table 2: Aircraft Distribution in a Beam Dwell

Complementary parameters of the scenario are:

1. Beamwidth: the above 48 aircraft are distributed in a 3.5° sector.
2. GICB rate: 1 GICB per aircraft.
3. Minimum range: 5 NM.
4. Maximum range: 150 NM.
5. Scan rate: 4 seconds.

To relax the demand on the tracker accuracy, a guard of 12 μs is added between each response. The guard allows almost 1 NM error in the tracker estimation, which is loose.

The output of the algorithm for one realization of the scenario described is shown in Figure 3. The bars from below are the transmissions while the bar from above are the receptions. In this case, the schedule is composed by as much as 9 cycles. Relevant here is the elapsed time consumed for the entire schedule that is less than 14 ms.

The left peak in Figure 4 shows the normalized histogram of the elapsed time consumed by 5,000 random runs of the algorithm simulating 48 original

[5] Except for the guards to cover the estimates of the trackers.

[6] The consideration of the constraints over the working cycle of the active components of the radar is beyond the scope of this work.

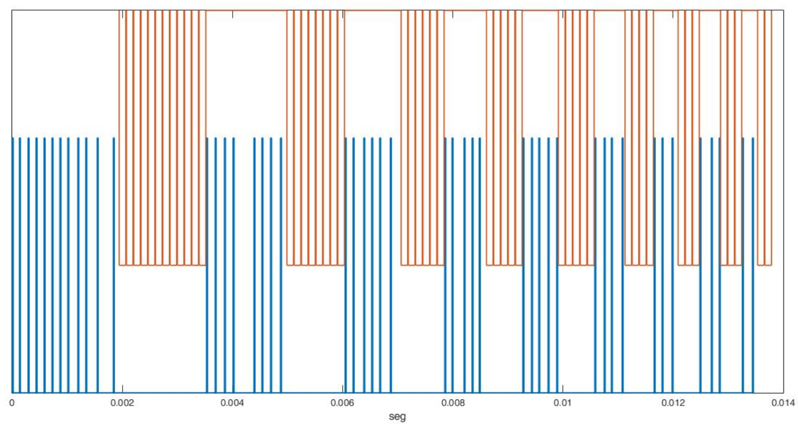

Fig. 3: Improperly nested scheduling for a 48 transactions scenario.

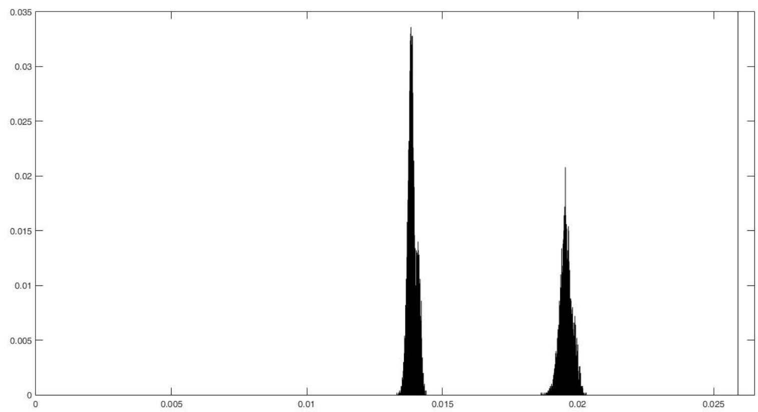

Fig. 4: Schedule/s elapsed time normalized histograms for 5,000 random run.

transactions. The mean value of this data is 13.9 ms, the standard deviation is 158.3 μs, the maximum value is 14.4 ms, and the minimum is 13.3 ms.

Given: beamwidth, $\theta = 3.5°$; scan period, $\tau = 4$s; fraction of dwell for Mode S transactions, $f = 2/3$. The available time for Mode S transactions in a dwell, A is,

$$A = f\tau\frac{\theta}{360°} = \frac{2}{3}\ 4\ \frac{3.5}{360}\ s = 25.9\ ms, \tag{6}$$

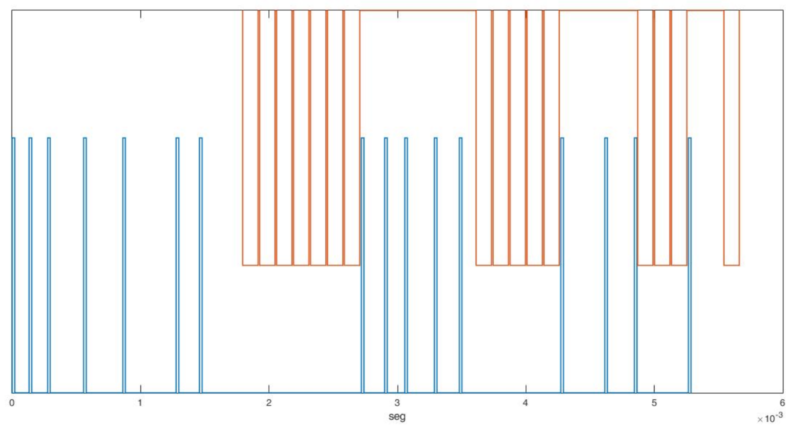

Fig. 5: Improperly nested 16 re-scheduled transactions from original scenario.

Rougly, it can be said that many times the schedule consumes more than 50 % of the available time (the continuous vertical line in the right side of Figure 4)[7]. As a consequence, two complete schedules are not allowed to be included in the same dwell, in several occasions.

Actually, the repetition of a transaction within the dwell is mandatory when not answer is received or any reception is pointed wrong as a consequence of a coding error detection [7].

Suppose that the initial probability of right reception of a transactions is $p_i = 68.38\%$. That means that 16 out of 48 receptions are misleading or wrong and the corresponding transactions have to be repeated during the present dwell in a new schedule. If that is possible, the final probability p_f for the transaction load in the dwell would be the prescribed [15],

$$p_f = p_i + (1 - p_i)p_i = 2p_i - {p_i}^2 = 90\% \tag{7}$$

The right peak of Figure 4 shows the elapsed time consumed by 5,000 random runs of the algorithm for two consecutive schedules, i.e., a first schedule of original 48 transactions and a second schedule of 16 transactions peaked out randomly from the original. The mean value of this data is 19.5 ms, the standard deviation is 227.4 μs, the maximum value is 20.2 ms, and the minimum value is 18.6 ms. As can be seen in Figure 4, the simulated data is far to the left of the available dwell time. Figure 5 is sample of a 16 transactions schedule consisting of 4 cycles and elapsing less than 6 ms.

[7] A more precise probability evaluation, possibly including inflation of Gaussian distribution models [16], is beyond the goals of this article.

5 Conclusion and Future Work

A preliminary improperly nested interleaving algorithm has been presented for the scheduling of Short Length Message transactions in the context of Mode S Secondary Surveillance Radar. The main characteristics of the algorithm are:

– Responses are in the same order as transmissions, for any schedule.
– Responses are linked one after the other without gaps, for any cycle.
– Cool-down time is always greater than zero, for any transaction.

The algorithm has been tested under a heavy load simulated scenario for 5,000 random runs. Elapsed time for the original 48-transaction schedule is barely greater than 50% of the available dwell time, making it possible to add a repetition schedule just shorter than the original. Then, for a probability of right reception as low as 68.38%, the re-scheduling of 16 out of 48 transactions is not only possible but also enough to accomplish a compound probability of 90% as prescribed [15].

Future work may include:

– Analysis of the requirements that the algorithm imposes under heavy load to the radar active components used during transmission.
– Modification of the algorithm to incorporate Long Length Messages as well.
– Study of the functional relation among cool-down, energy and distance between the radar and the aircraft.
– Determination of Gaussian bounding distributions from sample distributions of elapsed times.

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