Mode-S Radar Interrogation Algorithm Design for Dense Air Traffic Environment

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Abstract. *The increasing trend in air traffic density will continue in the near future with the addition of different aerial vehicles. Before the Mode-S protocol, Mode A and Mode C were in use; however, the Mode A/C configuration was only usable in sparsely dense air traffic. One of the useful features of Mode-S is the ability of probabilistic interrogation. However, there has not yet been a sophisticated algorithm for many close aircraft. Considering a futuristic air environment with a swarm of drones and airbuses equipped with transponders, we utilized the probabilistic interrogation feature of Mode-S and designed an algorithm. The proposed algorithm is able to collect close aircraft information in a relatively short time. There has also been created a high-level Mode-S uplink and downlink communication simulator in order to exchange all-call communication and record the algorithm's performance in terms of time and number of interrogations sent.*

Keywords

Garbling, lockout, Mode-S, stochastic interrogation

1. Introduction

The Mode-S (Selective) civilian communication system being used in secondary surveillance radars with 1030 MHz interrogation and 1090 MHz reply frequencies was first introduced in the 1970s by MIT Lincoln Laboratory and improved through the 1980s and 1990s. Prior to the Mode-S protocol, Mode A and Mode C were in use; however, this configuration was only usable in sparsely dense air traffic [1]. The reason is that all SSR (secondary surveillance radar) replies stack in the same frequency band; hence all aircraft signals being detected in the same antenna beam overlap with each other, and this phenomenon is known as garbling in general. When the 1090 MHz band is shared with both the Mode-S, ADS-B, and Mode A/C systems, there occurs FRUIT (false replies unsynchronized in time) which is co-channel interference due to dense environments [2].

Mode A and Mode C give information about interrogated aircraft's squawk code (4 octal digits) and altitude, respectively [3]. Besides mentioned traditional SSR abilities, Mode-S provides enhanced surveillance and datalink to ground control stations to be able to monitor aircraft with more capability.

Even operations with Mode-S systems cannot avoid garbling problems in the dense air traffic regions in terms of traffic since there occur close encounters between different aircraft within a close range, which is five nautical miles usual standard for horizontal separation, and around 2000 feet (~0.38 NM) for vertical separation [4]. These close scenarios can be caused by different sources such as lack of capacity of the coverage, weather conditions, military activities, airline decisions, etc. [5]. Another reason for having a highly dense air environment with close encounters is that there is an immense increase in air traffic demand and the number of aircraft registered. According to an annual report by EUROCONTROL, total flights will increase by an average of 1.9% per year over the next years, reaching a total of 11.6 million flights in 2023 [6]. Furthermore, forecasted IFR (instrument flight rules) movements per traffic zone tell that there is an upward trend in all states of the eurozone states in terms of air traffic density through 2024 [7]. Another reason for seeing many more aircraft on the skyline is that the cost of air traffic management is relatively disconnected from the air traffic, and this allows for the introduction of more registered aircraft [8]. Speaking of registered aircraft, the EU continues to develop the controlled inclusion of unmanned aerial vehicles in the air environment with its U-space project. This project offers UAS (unmanned aircraft systems) traffic management (UTM) to integrate UAS into air traffic management (ATM) [9].

There has been numerous research parallel to the increasing number of transponder-equipped drones for the last decade to provide airspace safety [10–12]. The increase in registered aircraft, including unmanned aerial vehicles, forces authorities to revise regulations such as RPAS (remotely piloted aircraft systems) [13]. The number of drones in urban and rural airspaces will also amplify when passenger transportation [14], package delivery [15], agricultural surveillance and air cargo [16] are taken into account. From a military standpoint, border monitoring, landmine detection, logistic security, and military mission delivery require more drone injection into the airspace [17], [18].

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Therefore, the future of air traffic will be crowded with UAS inclusion, and this requires new techniques and utilities in communication systems in order to detect aircraft in the dense air traffic regions rapidly.

At this stage, in order to reduce the time taken to detect aircraft in garbled replies, we come up with a probabilistic interrogation algorithm using already existing Mode-S features. In our approach, we use all-call interrogations with different probabilities in the uplink, and we interrogate with 1, 0.5, 0.25, 0.125, and 0.0625 probabilities according to our adaptive algorithm. By adaptively interrogating, a ground station operator can gather ICAO information of aircraft relatively fast in the dense garbled region from all-call replies. A different method can be interleaving scheduling for Mode-S transactions [19]. Inserting additional waiting times can diminish the heavy load of the dense air traffic in the all-call interrogation process. However, additional time and energy trade-offs appear as well.

Before proceeding into the proposed stochastic interrogation algorithm for air traffic control radar systems, the basic structures and fundamental formats of Mode-S systems are presented in this section.

1.1 Mode-S Interrogations

There are two types of Mode-S interrogations in terms of data length, short and long interrogations. Uplink interrogations operating at 1030 MHz frequency are sent by a DPSK (differential phase-shift keying) modulation scheme. A Mode-S interrogation contains a side lob suppression pulse (P_2) after the initial P_1 pulse and additionally a 56 (short) or 112 (long) bit data block. The first two pulses, P_1 and P_2, last 0.8 µs with a 2.0 µs interval between them [20]. The uplink Mode-S interrogation pulse sequence can be seen in Fig. 1.

An aircraft reply to the interrogation is modulated via pulse position modulation at 1090 MHz frequency, and the pulse sequence contains an 8 µs long preamble with 56 (short) or 112 (long) µs long data block. A 16-bit long preamble is fixed and always “1010000101000000” [21].

An air traffic control radar beacon system (ATCRBS) consisting of a rotating antenna and transponders typically sends an all-call interrogation around its environment. Replies to these all-call interrogations include the aircraft’s identity and the altitude, as usual. In traditional Mode A/C protocols, there are two pulses, namely P_1 and P_3, separated by 8 or 21 µs according to their length. A P_4 pulse lasting 1.6 µs is added to distinguish Mode-S all-call interrogations from Mode A/C ones [22].

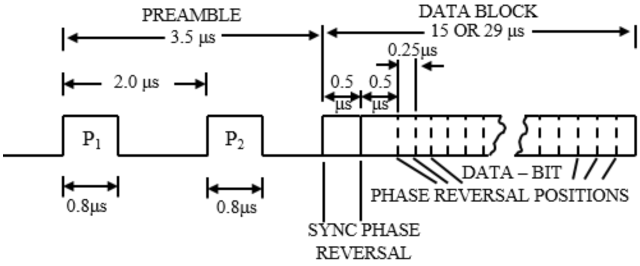

Fig. 1. Mode-S uplink pulse sequence [3].

1.2 Mode-S Formats

There are many uplink and downlink formats for Mode-S. The most commons are UF/DF 4, 5, 11, 20, and 21, as shown in Tab. 1.

UF/DF 20 and 21 contain Comm-B messages other than the payload, and there are different types of messages in Comm-B selection. The options can be depicted in Fig. 2.

UF/DF	Bits	Uplink	Downlink
0	56	Short air-to-air surveillance (ACAS)	Short air-to-air surveillance (ACAS)
4	56	Altitude Request	Altitude Reply
5	56	Identity Request	Identity Reply
11	56	Mode-S All-Call	Mode-S All-Call reply
16	112	Long air-to-air surveillance (ACAS)	Long air-to-air surveillance (ACAS)
17	112	-	Extended Squitter
18	112	-	Extended Squitter/non-transponder
19	112	-	Military extended squitter
20	112	Altitude request via Comm-A	Altitude reply via Comm-B
21	112	Identity request via Comm-A	Identity reply via Comm-B
24	112	Comm-C (ELM)	Comm-D (ELM)

Tab. 1. UF/DF formats of Mode-S [20].

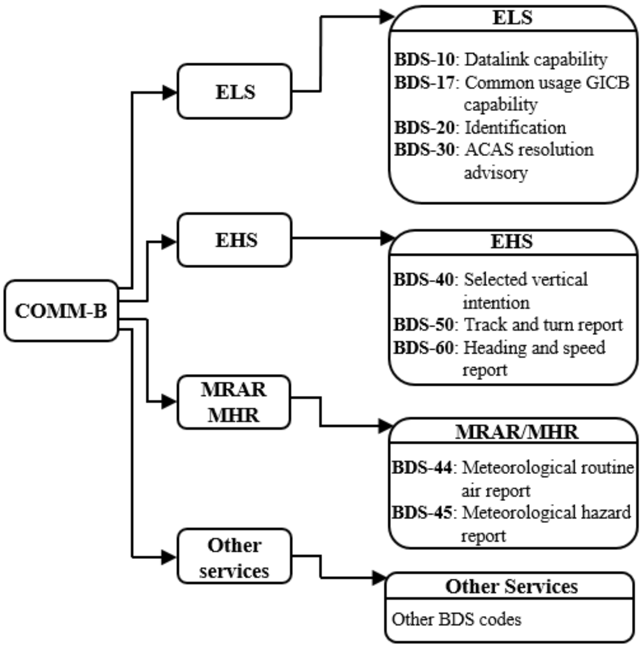

Fig. 2. Comm-B message types. ELS: Elementary Surveillance, EHS: Enhanced Surveillance, MRAR: Meteorological Routine Air Report, MHR: Meteorological Hazard Report [20].

Comm-B messages allow the ground station to gather specialized information other than position. More common BDS formats are BDS-10, 17, and 20, as they correspond to elementary surveillance. The availability and number of received Comm-B messages depend heavily on the density of air traffic and the rate of interrogations [23].

1.3 Selectivity and Garbling

Mode-S transponders have 255 different 56-bit data storage caches, which are called BDS (Comm-B data selector) registers. BDS registers content is updated periodically by a flight management system. Mode-S interrogators have two main tasks, one being to detect the replying aircraft and another being to extract more information from a detected aircraft [24], [25]. Using a unique ICAO (24-bit aircraft address) and getting all necessary information from the minimum number of replies reduce the interrogation density per aircraft. When the ground station is able to detect an aircraft with at most two interrogations, this results in avoiding Mode A/C overlaps, and hence selective interrogations could be further enabled.

Every region has a lockout map in an SSR Mode-S network. Lockout command is given by a ground station to a selected aircraft. The selected aircraft stops responding to other calls when it is in a lockout state [26]. The lockout map determines the area where the ground station locked up an aircraft. Generating a lockout map and managing these maps with multiple cities are challenging tasks since the number of locked-up aircraft is constantly changing [27], [28].

All-call interrogations are used for the initial communication when an aircraft enters the radar coverage. All-call interrogation signals don't have a specific destination; hence all non-locked-up aircraft have to respond to this call. A ground station periodically radiates all call interrogations with a maximum rate of 250 Hz [29]. After receiving a reply from an aircraft, the ground station extracts the specific aircraft's rough position and ICAO address. The next step is to follow the aircraft and interrogate it with "roll call." Roll-call interrogations are aircraft-specific interrogations once it is in a lockout state. This methodology helps ground stations to prevent unnecessary all-calls and reduce garbling effects.

The proposed Mode-S interrogation algorithm comes in handy at this stage since collecting all the all-call replies from aircraft in the dense region is an issue due to interrogating with a hundred percent probability.

2. Stochastic Interrogation Algorithm

The algorithm always works better in the dense air traffic regions than the current Mode-S radar uplink interrogation scheme, as the perception is that aircraft will not be closer than some limited distances. If any close encounter happens, then this situation will be short, and garbling effects will be temporary. However, the consideration in the developed algorithm is that the air traffic density will increase in the future, and there could be close encounters in the air with the addition of different aerial vehicles such as application-specific drones, airbuses, etc. By this logic, the current mechanism cannot deal with highly dense air environments as the number of aircraft increases. One possible solution to this futuristic dense air traffic problem in civilian aviation is to interrogate with constant probabilities such as 0.5, 0.25, 0.125, and 0.0625 as Mode-Selective uplink communication allows [21]. In this approach, constantly interrogating with 0.5 uplink requests would require too many interrogations while trying to detect all aircraft if the number of aircraft is too many. On the other hand, interrogating with 0.0625 is inefficient if there are not many aircraft in the target region. However, in dense environments, after detecting a number of aircraft by interrogating with a lower probability, we can fasten the detection process by increasing the probability contained in the interrogation. When we are getting a lot of garbling, we can decrease the probability of intercept. We propose an algorithm with these adaptive changes in such situations that will work much more efficiently than the static interrogation method. In our proposed method, we can estimate the density, low or high, of the remaining aircraft by their overall responses for one or more, depending on the control length and interrogations. For instance, if we are interrogating with 0.0625 and getting no replies, we should interrogate with a higher probability. In this algorithm, we are also using the feature of Mode-S; when aircraft is locked-out, it will not reply to interrogations until a particular time passes. Furthermore, our proposed algorithm will decrease the need for operator intervention.

The stochastic interrogation working principle is like this when the probability of intercept contained in the interrogation is p.

An aircraft replies with probability p.

An aircraft does not reply with probability $1-p$.

Theoretical calculations of static interrogations to detect all aircraft in the dense region can be seen by using binomial distributions with the below definitions:

$P_{\text{DETECTION}}$ = Probability of only 1 aircraft replying,
$P_{\text{NO-RESPONSE}}$ = Probability of getting zero responses,
P_{GARBLING} = Probability of collision due to multiple replies,

$$P_{\text{DETECTION}} = (1-p)^{N-1}\, pN\,, \tag{1}$$

$$P_{\text{NO-RESPONSE}} = (1-p)^{N}\,, \tag{2}$$

$$P_{\text{GARBLING}} = 1 - P_{\text{DETECTION}} - P_{\text{NO-RESPONSE}}\,, \tag{3}$$

$$P_{\text{GARBLING}} = 1-(1-p)^{N-1}\left[pN+(1-p)\right]. \tag{4}$$

Here, N is the number of aircraft in the dense region. The number of all-call interrogations with a static p probability of collecting all all-call replies from aircraft in the dense area becomes $M_{\text{DETECTION}}(p)$.

$$M_{\text{DETECTION}}(p) = \left(\frac{1-p}{p}\right)\sum_{k=1}^{N}\frac{1}{(1-p)^{k}\cdot k}\,. \tag{5}$$

As can be seen, the total number of interrogations steeply increases as N grows very large. When N is small, the minimum number of required interrogations is best with 0.5 static probability. Considering both small and large N cases, there needs to be an adaptive approach to utilize the best performances of all static probabilities from 0.5 to 0.0625. Therefore, an adaptive algorithm is required to solve this futuristic dense air traffic interrogation issue with no hardware change. Here, the pseudocode of the developed algorithm can be seen below.

Algorithm: Adaptive Probabilistic Interrogation

```
start procedure
Step 1  Interrogate with $P = 1$
    if number_of_aircraft_replied == 0 then
        return
    else if number_of_aircraft_replied == 1 then
        repeat Step 1
    else if number_of_aircraft_replied > 1 then
        go Step 2
    end-if
Step 2  Interrogate with $P = 1/2$
    if (number_of_aircraft_replied == 0 or number_of_aircraft_replied == 1) then
        go Step 1
    else if number_of_aircraft_replied > 1 then
        go Step 3
    end-if
Step 3 Interrogate with $P = 1/4$
    if number_of_aircraft_replied == 0 then
        go Step 2
    else if number_of_aircraft_replied == 1 then
        repeat Step 3
    else if number_of_aircraft_replied > 1 then
        go Step 4
    end-if
Step 4 Interrogate with $P = 1/8$
    if number_of_aircraft_replied == 0 then
        go Step 3
    else if number_of_aircraft_replied == 1 then
        repeat Step 4
    else if number_of_aircraft_replied > 1 then
        go Step 5
    end-if
Step 5 Interrogate with $P = 1/16$
    if number_of_aircraft_replied == 0 then
        go Step 4
    else if (number_of_aircraft_replied == 1 or number_of_aircraft_replied > 1)  then
        repeat Step 5
    end-if
end procedure
```

In the above pseudocode, the control length is 1. This means that when there is no reply for only one interrogation, we increase the probability of interrogation (POI), or when garbling happens, we decrease the POI. When control length is n, after n consecutive interrogations with no reply, we increase the POI. For probabilities 1 and 0.0625, some exceptions exist. Also, for probability 0.5, when detection occurs, we increase the POI again. Typically, for detection cases, there is no probability change.

2.1 Performance of the Algorithm

The algorithm runs with three different parameters for each Mode-S SSR specifications, namely pulse repetition frequency, RPM, and beam-width. The selected parameters are given in Tab. 2. These parameters are selected according to the most common values used in industrial airport radar antennas [30].

Parameter	Selected Values
PRF (Hz)	[150, 225, 300]
RPM (1/min)	[6, 10, 15]
Beam-width (degree)	[1.2, 1.8, 2.4]

Tab. 2. Basic Mode-S SSR specifications that are used in simulations.

Monte Carlo simulation with 1000 iterations is run for each number of aircraft ranging from 2 to 20; therefore, a total of $3 \times 3 \times 3 \times 19 = 513$ combinations is investigated in the results. Both our adaptive probabilistic interrogation algorithm and theoretical static interrogations are simulated to compare the performance in terms of time spent detecting all aircraft in the dense air environment. The time spent collecting all ICAO addresses during all-call interrogations and the mean number of interrogations to receive aircraft replies one by one without garbling are the most important metrics to consider.

Using the proposed algorithm and static interrogations in Monte Carlo simulation in order to compare the performance of these approaches in terms of the number of all-call interrogations, the results can be seen in Fig. 3.

The graph is divided into three different parts according to the density of the aircraft in the target area. Interrogating with static 0.5 probability all-calls gives the best performance in the less dense blue part since the garbling effects are diminished due to few numbers of aircraft. Using low probabilities such as 0.125 or 0.0625 to detect a few aircraft in the blue part happens to be an inefficient method. Interrogating with static 0.25 probability gives the best result in the dense, orange part. However, interrogation with static 0.125 or 0.0625 comes on top in the densest, green part in terms of performance since the number of aircraft is too many and garbling effects are immense in low probabilistic all-calls. Considering all the static interrogation approaches, they all tend to give good performances within defined colored parts.

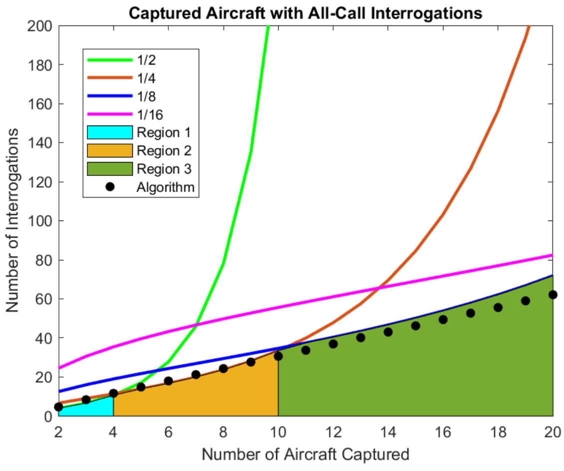

Fig. 3. Overall performance of adaptive algorithm vs static interrogations.

However, the proposed algorithm provides the best results when there are more than 10 aircraft in the dense environment, and moreover, it comes second best when there are few aircraft.

2.2 Effects of Basic Radar Specifications on Performance

Simulation results of adaptive interrogation algorithm in terms of different RPM, PRF, and BW parameters are shown in Fig. 4, 5, 6.

In all three figures, the time spent to detect all aircraft in the dense garbled region increases as the number of aircraft increases. Here, the performance metric is the time rather than the number of interrogations, and the time spent per pulse, T_{p} and total time spent for complete interrogation, T_{ci} are calculated as follows:

$$T_{\mathrm{p}} = \frac{1}{PRF}, \tag{6}$$

$$T_{\mathrm{ci}} = Number\ of\ completed\ interrogations \times T_{\mathrm{p}}. \tag{7}$$

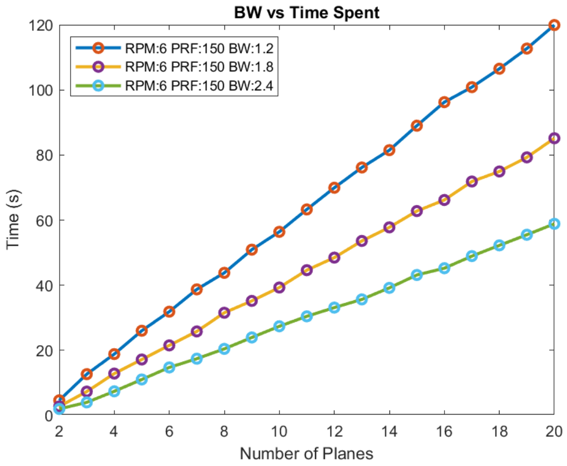

Fig. 4. Effect of beam-width on performance.

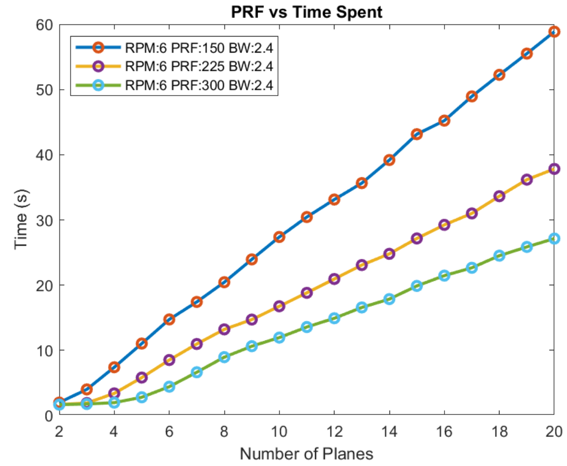

Fig. 5. Effect of PRF on performance.

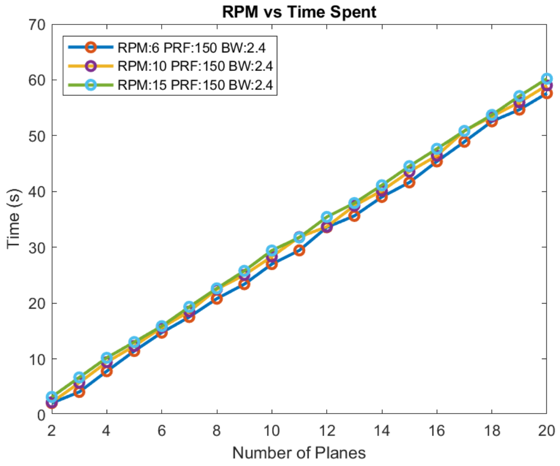

Fig. 6. Effect of RPM on performance.

As observed in Monte Carlo simulations with 500 iterations, the number of interrogations to detect all aircraft is not affected by parameter changes. For this reason, since the increase in PRF will shorten the time taken for interrogation, the total time spent will also decrease. The situation is similar in the beam-width case: As the increase in beam-width will increase the number of interrogations per aircraft in one tour, the number of tours taken will be shortened, which will shorten the total elapsed time. The RPM indicates how many seconds it takes to complete a lap. For this reason, PRF is divided by RPS (round per second) to find the total number of pulses sent in each round. To find the number of pulses in each beam, the total number of pulses in one round is divided by the total number of beams. Although the increase in RPM causes the antenna to rotate faster, we cannot say that there is a dominant correlation between the total interrogation time and RPM since it reduces the number of pulses in a beam.

For selected parameters, the total time spent is shown in Fig. 7. The proposed algorithm performs the best after the number of aircraft exceeds 10. It is observed that it gives very close to the best results in other places.

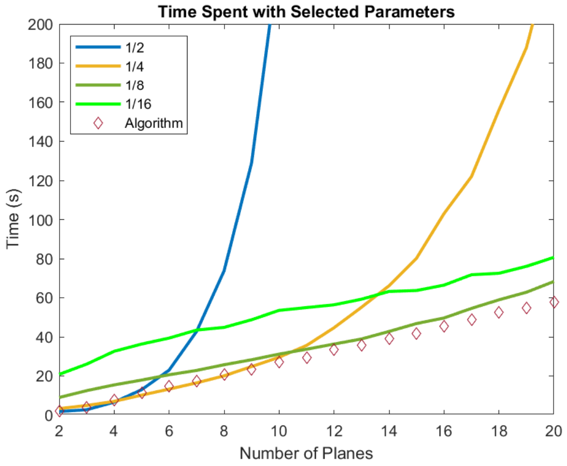

Fig. 7. The performance of the algorithm and static methods with selected parameters, i.e., PRF: 150 Hz, BW: 2.4 degrees, and RPM: 6 min^{-1}.

2.3 Limited Lockout

The lockout condition is that when an aircraft replies to an all-call message, the ground station locks up that aircraft in order to interrogate with roll-call messages, and this lockout duration takes approximately 18 seconds [29], [31]. During this lockout duration, we do not interrogate the detected aircraft once again with all-call uplink requests; therefore, we deduce that we found an aircraft in the dense air traffic region, and we shall not interrogate it with all-call messages. Once the eighteen-second lockout duration ends, we interrogate that specific aircraft again if it reenters the radar coverage area. By doing this, we take into account re-entries to the radar coverage in the vicinity of sections where two different ground stations intersect with each other's coverages.

In Fig. 8, the performances are given in terms of total time spent using selected parameters. Our adaptive algorithm also works as the second best most of the time in different density regions. Nevertheless, our adaptive algorithm comes on top regardless since the information about the number of aircraft in the region is not required, and this is handy for the operator in the ground station. An additional improvement can be made by taking care of entering and exiting time instances of an aircraft in the dense region rather than just interrogation probability switching.

In addition to the lockout condition, there is also a lockout override scenario in which the interrogator forces a transponder to reply to all all-calls. Stochastic interrogation needs to be used to avoid garbling in lockout override operations. This method is called stochastic lockout override acquisition (SLO) and is used when radar coverage clusters of different ground stations with the same ICs (interrogator code) overlap with each other [32]. While implementing SLO, the ground station (GS) uses the different probability of reply (PR) fields to avoid RF pollution since GS will receive an immense amount of replies due to overriding. The PR field is 4 bits in the uplink scheme, and it can take numbers from 8 to 12 in binary [33].

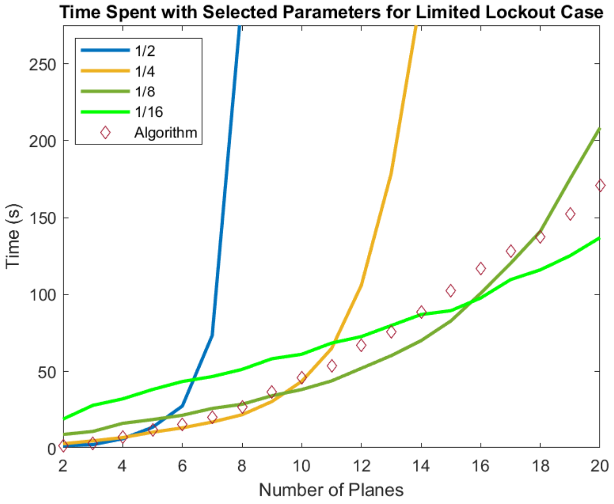

Fig. 8. The performance of the algorithm and static methods with selected parameters for limited lockout case, i.e., PRF: 150 Hz, BW: 2.4 degrees, and RPM: 6 min^{-1}.

3. Conclusion and Discussion

The time spent or the number of interrogations sent while gathering ICAO addresses of all aircraft in the dense region varies for the different number of aircraft. The statistical performance results of the 0.5, 0.25, 0.125, and 0.0625 probability strategies, including the proposed algorithm, in terms of the number of all-call interrogations, can be seen in Tab. 3.

For regions 1 (2–4 aircraft) and 2 (5–10 aircraft), the proposed algorithm gets better as the number of aircraft increases in the region, and for region 3 (11–20 aircraft), the proposed algorithm clearly outperforms other static approaches. These results show that the proposed algorithm can be quite useful when considering future needs and ATM (air traffic management) or UTM (UAS traffic management) control strategies. Such air traffic control strategies are required as the air traffic environment becomes denser year after year. As some UAVs start to use Mode-S communication protocols as well, e.g., ads-95 ranger drones of the Swiss Airforce, and the need for ICAO registration of this type of vehicle increases as they enter airspaces [34]. Therefore, the increase in air traffic reveals the importance of probabilistic interrogations in Mode-S protocol. In this paper, the theoretical and computational results of probabilistic interrogations are obtained. At the same time, an algorithm is proposed that both reduces the operator requirement and works well without many static interrogations. The proposed algorithm works adaptively according to the density of the aircraft. This adaptive operating principle will facilitate the adaptation to future dense air traffic environments and reduce the detection time of the aircraft in air control and monitoring applications.

Number of aircraft	0.5 method	0.25 method	0.125 method	0.0625 method	Algorithm
2	4.00	6.67	12.6	24.5	4.7
3	6.67	9.03	16.0	30.6	8.3
4	10.7	11.4	19.0	35.4	11.6
5	17.1	13.9	21.8	39.6	14.9
6	27.7	16.7	24.3	43.2	18.0
7	46.0	20.0	26.9	46.6	21.2
8	78.0	23.7	29.4	49.8	24.3
9	135.0	28.1	32.0	52.8	27.6
10	237.3	33.5	34.7	55.6	30.6
11	423.5	40.0	37.4	58.4	33.7
12	764.8	47.8	40.3	61.1	37.0
13	1395	57.5	43.4	63.8	40.0
14	2565	69.6	46.7	66.4	43.0
15	4749	84.5	50.1	69.0	46.2
16	8845	103.2	53.8	71.7	49.4
17	16556	126.7	57.8	74.3	52.7
18	31119	156.2	62.1	77.0	55.6
19	58714	193.6	66.8	79.7	59.0
20	111140	240.9	71.8	82.4	62.1

Tab. 3. Number of interrogations to detect aircraft for the constant 0.5, 0.25, 0.125, and 0.0625 probability methods and the proposed algorithm.

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References

[1] BAKER, J. L, ORLANDO, V.A., LINK, W.B., et al. Mode S system design and architecture. *Proceedings of the IEEE*, 1989, vol. 77, no. 11, p. 1684–1694. DOI: 10.1109/5.47731

[2] INTERNATIONAL TELECOMMUNICATION UNION. *Reception of Automatic Dependent Surveillance Broadcast via Satellite and Compatibility Studies with Incumbent Systems in the Frequency Band 1 087.7-1 092.3 MHz.* Geneva: ITU, 2017. Report ITU-R M.2413-0

[3] BEASLEY, B. *Understanding Mode S Technology.* [Online] Cited 2012-10-10 Available at AvionTEq: https://www.avionteq.com/document/Understanding-Mode-S-technology.pdf

[4] EUROPEAN ORGANIZATION FOR THE SAFETY OF AIR NAVIGATION. *Conflict-Free Direct Routings in European Airspace*. March 1997. EEC Report No. 308.

[5] STANDFUSS, T., SCHULTZ, M. Performance assessment of European air navigation service providers. In *2018 IEEE/AIAA 37th Digital Avionics Systems Conference (DASC)*. London (UK), 2018, p. 1–10. DOI: 10.1109/DASC.2018.8569839

[6] EUROPEAN ORGANIZATION FOR THE SAFETY OF AIR NAVIGATION. *EUROCONTROL Annual Report 2016.* 3 August 2017.

[7] EUROPEAN ORGANIZATION FOR THE SAFETY OF AIR NAVIGATION. *EUROCONTROL Five-Year Forecast 2020-2024.* 4 November 2020.

[8] EUROPEAN ORGANIZATION FOR THE SAFETY OF AIR NAVIGATION. *EUROCONTROL Data Snapshot #8 on the Costs of Air Traffic Management in Europe.* 23 March 2021.

[9] CABALLERO, R. M. UAS Bulletin #2. In *European Civil Aviation Conference (ECAC).* France, December 2021.

[10] HAESSIG, D. A., OGAN, R. T., OLIVE, M. "Sense and avoid" - What's required for aircraft safety. In *IEEE Southeastcon.* Norfolk (VA, USA), 2016, p. 1–8. DOI: 10.1109/SECON.2016.7506724

[11] MINUCCI, F., VINOGRADOV, E., POLLIN, S. Avoiding collisions at any (low) cost: ADS-B like position broadcast for UAVs. *IEEE Access*, 2020, vol. 8, p. 121843–121857. DOI: 10.1109/ACCESS.2020.3007315

[12] JONÁŠ, P., JANČÍK, M., HOLODA, Š., et al. Impact of SUAS equipped with ADS-B on 1090 MHz environment. In *2020 New Trends in Civil Aviation (NTCA).* Prague (Czech Republic), 2020, p. 63–67. DOI: 10.23919/NTCA50409.2020.9291095

[13] BATUWANGALA, E., KISTAN, T., GARDI, A., et al. Certification challenges for next-generation avionics and air traffic management systems. *IEEE Aerospace and Electronic Systems Magazine*, 2018, vol. 33, no. 9, p. 44–53. DOI: 10.1109/MAES.2018.160164

[14] DOOLE, M., ELLERBROEK, J., HOEKSTRA, J. M. Investigation of merge assist policies to improve safety of drone traffic in a constrained urban airspace. *Aerospace,* 2022, vol. 9, p. 1–25. DOI: 10.3390/aerospace9030120

[15] KELLERMANN, R., BIEHLE, T., FISCHER, L. Drones for parcel and passenger transportation: A literature review. *Transportation Research Interdisciplinary Perspectives,* 2020, vol. 4, p. 1–13. DOI: 10.1016/j.trip.2019.100088

[16] SHRESTHA, R., BAJRACHARYA, R., KIM, S. 6G enabled unmanned aerial vehicle traffic management: A perspective. *IEEE Access,* 2021, vol. 9, p. 91119–91136. DOI: 10.1109/ACCESS.2021.3092039

[17] YOO, L. S., LEE, J. H., KO, S. H., et al. A drone fitted with a magnetometer detects landmines. *IEEE Geoscience and Remote Sensing Letters*, 2020, vol. 17, no. 12, p. 2035–2039. DOI: 10.1109/LGRS.2019.2962062

[18] JAN, S. U., KHAN, H. U. Identity and aggregate signature-based authentication protocol for IoD deployment military drone. *IEEE Access*, 2021, vol. 9, p. 130247–130263. DOI: 10.1109/ACCESS.2021.3110804

[19] KOGA, T., MORI, K. Autonomous lockout map construction technique for secondary surveillance radar Mode S network. In *2010 IEEE Radar Conference*. Arlington (VA, USA), 2010, p. 1439–1443. DOI: 10.1109/RADAR.2010.5494389

[20] SUN, J. *The 1090 Megahertz Riddle: A Guide to Decoding Mode S and ADS-B Signals.* Delft: TU Delft OPEN Publishing, 2021. ISBN: 978-94-6366-402-8 DOI: 10.34641/mg.11

[21] EUROPEAN ORGANIZATION FOR THE SAFETY OF AIR NAVIGATION. *Principles of Mode S Operation and Interrogator Codes.* 2003, March 18.

[22] MATEU, J. *RADIOLOCATION: Secondary Surveillance RADAR (SSR), Air Traffic Control Radar Beacon System(ATCRBS).* [Online] 2016. Retrieved from Universidad Politecnica de Catalunya Barcelonatech: UPCommons: https://upcommons.upc.edu/bitstream/handle/2117/340881/SSR.pdf?sequence=1&isAllowed=y

[23] SUN, J., VU, H., ELLERBROEK, J., et al. pyModeS: Decoding Mode-S surveillance data for open air transportation research. *IEEE Transactions on Intelligent Transportation Systems,* 2020, vol. 21, no. 7, p. 2777–2786. DOI: 10.1109/TITS.2019.2914770

[24] EUROPEAN ORGANIZATION FOR THE SAFETY OF AIR NAVIGATION. *MODE-S Specific Services and Data Link Test Bench*. 1998, April.

[25] KOGA, T. Classification of Mode S transponders by datalink capability. In *2014 Integrated Communications, Navigation and Surveillance Conference (ICNS) Conference Proceedings*. Herndon (VA, USA), 2014, p. O3-1–O3-7. DOI: 10.1109/ICNSurv.2014.6820008

[26] BODART, J. *Mode S Surveillance Principle.* [Online] Cited 2019-02-26. Available at EUROCONTROL: https://www.icao.int/MID/Documents/2019/MICA/MICA-MID%20-%20WP%2002%20-%20Mode%20S%20Surveillance%20Principle.pdf

[27] EUROPEAN ORGANIZATION FOR THE SAFETY OF AIR NAVIGATION. *EUROCONTROL Specification for European Mode S Station (EMS).* 2021, December 14.

[28] BODART, J. *Radar Programming (MIP*). [Online] Published 2019-02-26. Available at EUROCONTROL: https://www.icao.int/MID/Documents/2019/MICA/MICA-MID%20-%20WP%2012%20-%20Radar%20programming%20-%20MIP.pdf#search=radar%20programming%20MIP

[29] EUROPEAN ORGANIZATION FOR THE SAFETY OF AIR NAVIGATION. *Mode S transponder in an airport/A-SMGCS environment - Clarification.* [Online] Published 2005-05-03. Available at: https://www.eurocontrol.int/publication/mode-s-transponder-airporta-smgcs-environment-clarification

[30] PAYDAR, M. *SSR Mode S Coordination Issues.* [Online] Published 2010-08. Available at ICAO.INT:

https://www.icao.int/WACAF/Documents/Meetings/2011/asi_ws/pp1_ssr_modes_coordination.pdf

[31] BRIA, O. N., GIACOMANTONE, J., VILLAGARCÍA WANZA, H. A. Interleaving scheduling algorithm for SLM transactions in Mode S surveillance radar. In *XXIV Congreso Argentino de Ciencias de la Computación.* La Plata (Argentina), 2018, p. 1–16. ISBN: 978-950-658-472-6 DOI: 10.1007/978-3-030-20787-8_21

[32] MAZÚCH, P., KLECUN, R. Identification of an aircraft with the mode-S. *Acta Avionica*, 2013, vol. XV, no. 27, p. 1–6. ISSN: 1335-9479

[33] KOGA, T., UEJIMA, K. Results of validation of SSR mode S interrogator identifier code coordination. In *2009 IEEE/AIAA 28th Digital Avionics Systems Conference*. Orlando (FL, USA), 2009, p. 4.D.6-1–4.D.6-7. DOI: 10.1109/DASC.2009.5347481

[34] SCHAFER, M., STROHMEIER, M., SMITH, M., et al. OpenSky report 2016: Facts and figures on SSR mode S and ADS-B usage. In *2016 IEEE/AIAA 35th Digital Avionics Systems Conference (DASC)*. Sacramento (CA, USA), 2016, p. 1–9. DOI: 10.1109/DASC.2016.7778030

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