Distributed Location Detection Algorithms using IoT for Commercial Aviation

Amlan Chatterjee*, Hugo Flores*, Soumya Sen†, Khondker S. Hasan‡, Ashish Mani§
*Department of Computer Science, California State University Dominguez Hills, Carson, CA USA
†A.K. Choudhury School of IT, University of Calcutta, Kolkata, WB India
‡College of Science and Engineering, University of Houston-Clear Lake, Houston, TX, USA
§Department of EEE, Amity University, Noida, UP India
achatterjee@csudh.edu, hflores27@toromail.csudh.edu, iamsoumyasen@gmail.com, HasanK@uhcl.edu, amani@amity.edu

***Abstract*—Detecting precise location of aircraft during the entire flight duration is a challenge in the domain of commercial aviation. Using radar and other available technology, flights operating entirely over land can be tracked easily. However, with long haul intercontinental flights, where majority of the flight path is over water bodies and out of range of radar, detecting the location of aircraft at all times is a challenge. In recent times, there have been disasters in commercial aviation, where an aircraft has gone missing. This has a huge social and financial impact on the specific airline and commercial aviation in general. Therefore, in this paper we study the problem of location detection for commercial aircraft and methods to improve location detection over any terrain the flight path traverses. We propose techniques based on the Internet-of-things (IoT) model for aircraft, where the aircraft can communicate with each other within a certain range. We introduce distributed algorithms to detect location using such methods that work effectively when the aircraft is outside the range of radar and on an oceanic route. Our results show that using the proposed methods, the precise location of all aircraft, including those inter-continental flights, can be tracked to a higher degree. Techniques to minimize the communication overhead introduced due to the proposed methods are also provided.**

***Index Terms*—IoT, distributed location detection, aviation, communication, commercial aviation**

I. INTRODUCTION

Constant communication of aircraft with air traffic control (ATC) tower is essential in the domain of commercial aviation. Determining the exact location of the aircraft at all times during a flight is essential for flight path planning, guidance to the pilots, safety etc. There are radar and LIDAR based techniques that can detect the precise location of aircraft provided the flight path is completely over land mass. However, such techniques do not work when the aircraft path is over large water bodies like an ocean during inter-continental flights. In recent times, Malaysia Airlines flight 370 (MH 370) was declared untraceable after the aircraft was not detected by the expected ATC towers along the flight path [10]. Such an incident, which might involve safety concerns for the passengers and the aircraft, can be avoided if the aircraft is tracked at all times during the flight.

There are about 5,000 flights in the airspace of the United States at any given time. With approximately 19,000 operational US airports that operate upwards of 43,000 flights daily, the total number of flights handled by the Federal Aviation Agency (FAA) was more than 16 million in 2016 [15]. The continued growth of commercial aviation and maintaining the stringent requirements of operation have poised a challenge that has to be addressed using advancements of technology.

IoT frameworks have been developed and are already in use in major airports to help with luggage handling, tracking and enhancing passenger experience among others [14][18]. In this paper, we propose an IoT framework for commercial aviation. We introduce distributed algorithms to detect the location of aircraft at all times, even while traveling on oceanic routes. Our methods are based on the model of information exchange in the form of messages between the communication devices on the aircraft within a specific distance of each other. In addition to providing details about the aircraft operation, the devices on flights also gather and store huge amounts of data along the flight paths during the travel which are also relayed to the ATC tower when there is communication channel open between the aircraft and an ATC tower. The analysis of these data sets provide hitherto unavailable insights into improving the efficiency of flight operations [4][5][6]. Hence, maintaining constant communication between the aircraft and ATC tower with location information is essential and can potentially be utilized to improve a number of aspects of commercial aviation. These devices, which are a part of the IoT framework, communicate with other such devices on nearby aircraft, and also with any ATC tower within range. Therefore, using variable number of hops, messages from any aircraft can be forwarded via a number of other aircraft to an ATC tower to keep track of the location. The network bandwidth requirement for the communication can be reduced by compressing the transferred data, but the process would add to the latency and computational overhead [3][13].

The outline of our paper is as follows. In Section II, we present information on previous work related to different techniques for aircraft location detection. In Section III, we introduce an IoT framework for commercial aviation. Algorithms for different scenarios to detect location using IoT enabled devices abroad aircraft are introduced in Section IV. Experimental results of the implementation of the introduced algorithms for location detection is presented in Section V. Conclusion and future work is discussed in Section VI.

II. RELATED WORK

The use of the IoT paradigm to track objects has been proposed extensively. However previous research do not focus on the subject of tracking aircraft rather than focus on the real time tracking of packages or other physical inventory in order to reduce costs and improve efficiency [9].

In aviation, the IoT paradigm has generally been limited to the realm of safety. Current application focus on monitoring aircraft components throughout their manufacturing process to ensure the parts are made correctly [1] or with monitoring components within the aircraft to ensure proper maintenance and function [8].

Using radar to track aircraft location has been proposed before. In addition, techniques to optimize radar detection of aircraft location also exist [19]; however, these methods do not work in radar shadow zones and clutter zones. There have been enhancements proposed to radar resulting in the usage of advanced technology such as LIDAR (Light Detection and Ranging) systems, but these would only work when the aircraft is traveling over land mass [16][17].

Related to aviation there are applications that perform analysis on airline data using IoT devices. Automatic dependent surveillance-broadcast (ADS-B) data exchanges between receivers and equipped aircraft have been analyzed to be used in applications including airspace and traffic monitoring [7].

Using IoT framework for detecting location of automobiles have been studied before. There are other distributed sensor and crowdsourcing applications in different domains that use similar basic principle [12]. There is previous research on remote tracking of automobiles via automobile-to-automobile and automobile-to-infrastructure is proposed to create an Intelligent Transportation System [2]. Although these are ideas based on using sensors on existing devices to track location, the challenges involved in commercial aviation are fundamentally different. In this paper, we consider scenarios of detecting location of aircraft using both direct and indirect message transfer between nearby aircraft and ATC towers. To the best of our knowledge, this is the first work that proposes using IoT based techniques to detect location of aircraft.

III. IOT FRAMEWORK FOR COMMERCIAL AVIATION

Tracking the location of aircraft has generally been done using radar based technologies from ATC towers. These methods are robust, and can provide precise location of aircraft whenever there is a line of sight from the ATC tower to the aircraft. However, placement of radars at regular intervals is required for these methods to work. Now, in the case of aircraft traveling over large water bodies, like an ocean for inter-continental flights, the lack of radars over a large area due to absence of land mass renders these methods unusable. As shown in Fig. 1, flights within the range of radars at ATCs, in this case Aircraft1 (AC1) and Aircraft3 (AC3), can be tracked; however, for flights over the ocean, in this case Aircraft2 (AC2), cannot be tracked and the precise location of the aircraft would be uncertain.

In this Section, we introduce the IoT framework for commercial aviation. There are a number of sensors and communication devices already available on aircraft that measures various parameters and sends data over to communicating ATC towers. The IoT framework for commercial aviation consists of the different sensing and networking devices on aircraft that can communicate with each other automatically. Utilizing these devices, data can be exchanged between aircraft that are within the communication range of each other. Using multiple hops to forward the messages received from neighboring aircraft, information can be forwarded longer distances, and if possible ultimately to an ATC tower.

The conventional method for location detection using radar based at ATC towers is shown in Fig. 1. In this case, there is only communication between aircraft and ATC towers, but no connection between the aircraft. Hence, even though certain aircraft is within range of another one, it still cannot communicate any data with no channel available between aircraft.

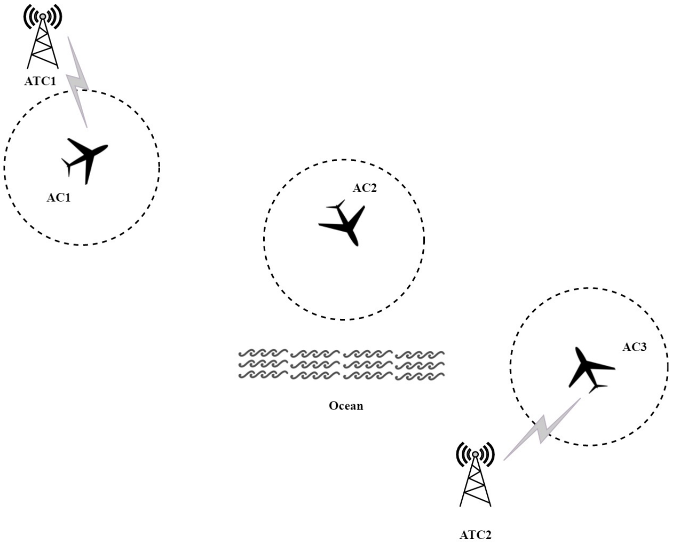

Fig. 1. Limited Location Tracking Over Water Bodies

An IoT based framework for commercial aviation is shown in Fig. 2. In this case, in addition to being connected to the ATC tower, the aircraft can communicate with each other if within range. Using this mechanism of automatic data exchange between devices on aircraft within a region, the issue of limited tracking of aircraft can be resolved in areas outside of radar zones. Consider the topology of aircraft and ATC towers as depicted in Fig. 2. Only the aircraft at the top and the bottom of the diagram i.e., AC1 and AC5 are within radar range of ATC towers ATC1 and ATC2 respectively, so can be tracked directly. All other aircraft are outside the range of detection using radar, and hence the location cannot be detected using radar based techniques. However, there are multiple aircraft within the region and in range of communication with other nearby aircraft. In this scenario, a chain of communication can be formed, where information about the location from one aircraft can be forwarded to nearby aircraft in the region, which in turn can deliver the message to it's neighbors ultimately reaching the ATC tower. Hence, the IoT framework is formed using communication between aircraft to exchange messages, as shown in Fig. 2.

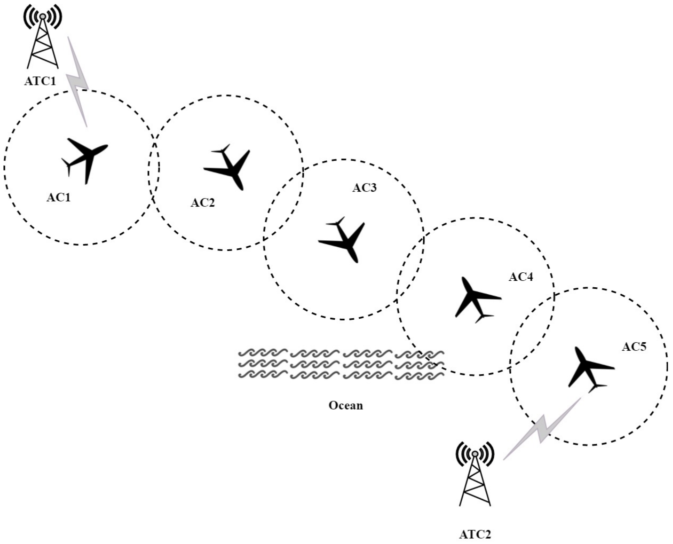

Fig. 2. IoT Framework for Continuous Flight Tracking

IV. DISTRIBUTED LOCATION DETECTION ALGORITHMS

In this Section, we discuss the different scenarios for location detection in commercial aviation, and introduce algorithms for each. The different algorithms are based on direct communication between the IoT devices on the aircraft.

For location detection of aircraft, there are mainly 2 problems at hand. First, the methods that are proposed should be able to maximize the percentage of time aircraft can be detected. Second, the communication overhead involved in the methods should be minimized.

Let the total time of flight be denoted by T_f, and the total time the flight can be tracked denoted by T_t. Therefore, the fraction of time the flight can be tracked, T_{tp} is given by,

$$T_{tp} = \frac{T_t}{T_f} \tag{1}$$

Hence, for a given time span, the objective of the algorithms would be to maximize the total tracking for all aircraft, given by the set $\{\lambda\}$, where $|\lambda| = n$, is given by,

$$\max \sum_{i=1}^{n} T_{tp_i}, \forall i \in \{\lambda\} \tag{2}$$

where, T_{tp_i} is the tracking percentage for Aircraft$_i$.

Let the number of messages sent or forwarded by Aircraft$_i$ be denoted by M_i. So, to reduce the communication overhead, the objective of the algorithms would be to minimize the total number of messages sent by aircraft in the given region, as given by,

$$\min \sum_{i=1}^{n} M_i, \forall i \in \{\lambda\} \tag{3}$$

The first scenario considered is the conventional tracking of flights using radar-based techniques. The aircraft is tracked using radar, stationed at ATC towers or other places, for the entire duration of the flight. The location data is updated regularly in a table, at the ATC, that stores all aircraft location. ATC towers then share this table with each other at predefined intervals of time to get a global perspective of location of all aircraft within a region. This technique is given in Algorithm 1.

Algorithm 1: Tracking flights with radar-based techniques

```
Input: Line of sight visibility of aircraft
Output: Location of aircraft
begin
    forall $T_i \in Flight_{time}$ do
        radarDetect ();
        updateLocation ();
        locationShareATC ();
    Exit ();
```

However, this technique is applicable for tracking of flights specifically over land. For flights traveling over water bodies, this algorithm does not perform well; it is usually able to track only about 150 miles of flight path over the ocean at the origin and destination locations, outside which it drops off the radar.

Considering the IoT framework for commercial aviation, aircraft exchange data through communicating devices. Therefore, for location detection algorithms, aircraft should be able to exchange location data. Hence, aircraft within a specific region share location with active data sharing i.e., send data automatically at periodic intervals. Each aircraft detects its own location using on-board Global Positioning System (GPS). Then, the location data is shared with all other aircraft within the region using the devices on the aircraft. Each aircraft would store location information about other aircraft in a location table locally. When all aircraft within the region complete sharing the data, each aircraft updates the local table with tracking information. Hence, using IoT framework location information can be exchanged between aircraft and this method is given in Algorithm 2.

Algorithm 2: Location detection with active data sharing

```
Input: Aircraft within specific region
Output: Location sharing among aircraft
begin
    forall $T_i \in Flight_{time}$ do
        locationGPS ();
        forall $Aircraft \in Range$ do
            locationShareAircraft ();
        forall messageLocationData do
            updateLocationTable ();
    Exit ();
```

Algorithm 2 describes the method to actively share data between aircraft. In addition, aircraft should also be able to detect precise location of nearby aircraft where active sharing is not supported i.e., for some reason the device for reporting location on other aircraft is not operational. In this case, using triangulation techniques [11], the location of the aircraft can be detected. The aircraft can use the on-board Traffic Collision Avoidance System or TCAS, to identify nearby aircraft approximate location. Once three aircraft can identify the approximate position of the aircraft, triangulation would assist in determining the precise location. Now, multiple aircraft can share location data about specific aircraft when the values are estimated. Then using all the isolated information together, the precise location can be mapped; this is essentially the basic method for distributed location detection. Now, in the scenario where more than one group of three aircraft determine the location of the non-communicating aircraft, the data can be broadcast within the region, and based on the data, the one approximate location which matches the maximum number of groups would be chosen as the appropriate value. This method is provided in Algorithm 3.

Algorithm 3: Passive location detection with IoT device communication failure

```
Input: Aircraft within specific region
Output: Location of aircraft with failed communication
        device
begin
    forall $T_i \in Flight_{time}$ do
        forall $AC \in Range$ do
            detectNerarbyWithTCAS ();
            if location ← Algorithm 2 then
                updateLocationTable ();
        forall Aircraft not responding using Algorithm 2
          do
            exchangeInformation ();
            locationTriangulation ();
            updateLocationTable ();
        broadCastApproximatePosition ();
        selectAppropriateValue ();
    Exit ();
```

In the next scenario, we consider location detection using messages broadcast over the IoT based framework. All aircraft within a broad region is considered; the desired outcome of this broadcast technique is to share the location information among all aircraft and potentially with an ATC tower. In this case, each of the individual aircraft detects its own location using on-board GPS. Then, the location data is shared with all other aircraft within the region using a broadcast message. When all aircraft have completed sharing the data, each aircraft updates it's local table with tracking information received, and creates it's own global tracking table with information about all aircraft that it received via the messages. If the aircraft is unable to provide location information using active sharing, then the information is obtained using Algorithm 3 employing the passive sharing technique. Then in the next iteration, each aircraft broadcasts it's global tracking table, so that the data is forwarded to all aircraft within range. In this manner, location data from one aircraft is propagated to other aircraft, which are not in range, via a chain of messages formed by aircraft. If an aircraft is within the range of an ATC tower, it shares the global location table with the ATC tower. This method is given in Algorithm 4.

Algorithm 4: Location detection based on IoT broadcast

```
Input: Aircraft over a broad region
Output: Location sharing among aircraft and ATC tower
begin
    forall $AC \in Region\{\}$ do
        updateLocationTable () ← Algorithm 2;
    forall $T_i \in Flight_{time}$ do
        if predefinedTimeInterval then
            forall $AC_i \in Region\{\}$ do
                sendTableData ();
                receiveTableData ();
                updateGlobalLocationTable ();
                if IoTDeviceCommFailure() then
                    Algorithm 3;
        if withinATCRange then
            shareGlobalLocationTableATC ();
    Exit ();
```

The IoT based broadcast technique, given in Algorithm 4 is inefficient because of huge communication overhead due to exchange of large number of messages. This also contradicts one of the objectives of minimizing overhead as given in Equation 3. Therefore, we propose another algorithm where the location tracking is based on IoT multicast and limited hops, which addresses the issue of redundant communication. Once the location data for each aircraft is detected using the GPS or by passive sharing algorithm, the local location data table is updated. At predefined intervals, aircraft send their location data to neighboring aircraft. The messages are forwarded from one aircraft to another, but only when the number of hops of the original location message is less than the threshold. In this case, the number of messages being exchanged is drastically reduced. This method is given in Algorithm 5.

The communication overhead can be further reduced by forming clusters among the aircraft within specific range, and only multicasting messages that have been locally updated. Though this approach reduces the overhead of messages exchanged, it adds to the complexity of creating and maintaining a cluster where flights can dynamically join and leave.

V. EXPERIMENTAL RESULTS

In this Section, results of the implementation of the proposed algorithms using simulation techniques is discussed. The simulation is performed over a large area with the number of aircraft varying from 200 to 1000. The aircraft are introduced

Algorithm 5: Tracking with IoT multicast & limited hops

```
Input: Aircraft over a broad region
Output: Location sharing among aircraft and ATC tower
begin
    forall $AC \in Region\{\}$ do
        updateLocationTable () ← Algorithm 2;
    forall $T_i \in Flight_{time}$ do
        if predefinedTimeInterval then
            forall $AC_i \in Region\{\}$ do
                listenMessage ();
                forall $Message \in Region\{$ThresholdHops$\}$ do
                    updateSelectiveTable ();
                    cleanTable ();
                sendTableData ();
        if $AC \in ATCRange$ then
            shareLocationTableATC ();
    Exit ();
```

in a staggered manner over time to simulate flights departing from airports. The geographical area considered contains large water body, and is similar to the area between United States and Japan. The area under consideration is approximately 5000×5000 square miles. This specific area is chosen to simulate the flights, which include path over the oceans, since the proposed techniques can perform location detection on oceanic routes.

In our simulation, the following data is calculated: (a) Percentage of time the flights can be tracked without our methods; (b) Percentage of time the flights can be tracked using IoT based technique and broadcasting; (c) Percentage of time flights tracked within threshold number of hops and multicasting. In addition, for all the scenarios, the overheads of communication is also calculated. The scenario where IoT based techniques are not employed is referred to as Scenario A, the one where IoT based technique is used with broadcasting is referred to as Scenario B, and finally the scenario with IoT based technique and multicasting with limited number of hops for messages is referred to as Scenario C.

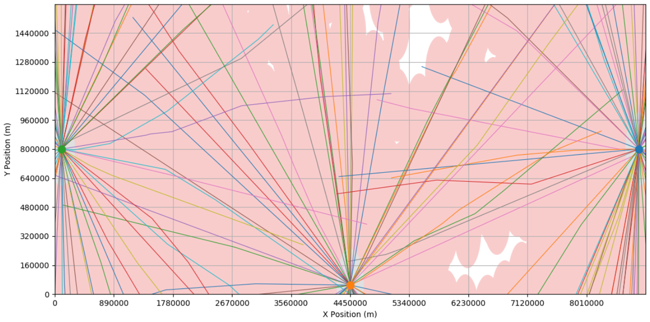

Fig. 3. Flight Patterns for Scenario A

Fig. 3 shows the flight patterns for Scenario A. The simulation is executed for 6 hours and there are total 200 aircraft considered. Using a time quantum of 120 seconds, the total messages sent is 29694.

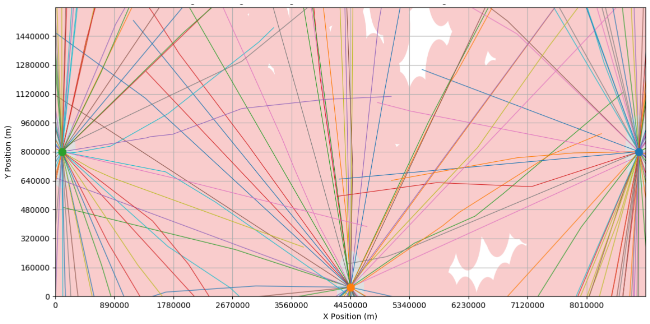

Fig. 4. Sample Flight Patterns for Scenario B

Similarly, Fig. 4 depicts the flight patterns for Scenario B, for 6 hours and 200 aircraft. Using the time quantum of 120 seconds, the total messages send is 1074504.

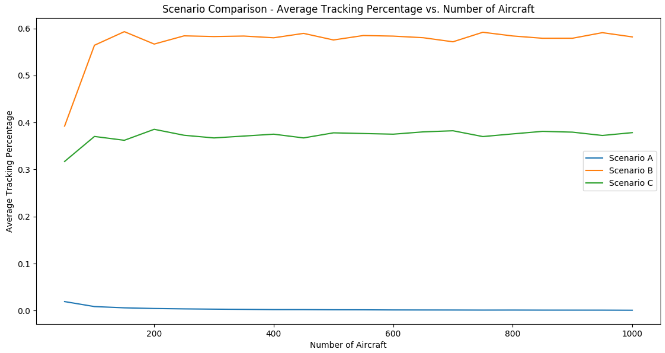

Fig. 5. Tracking comparison for different scenarios

According to Fig. 5, Scenario A is the simplest but least efficient way to track the position of aircraft. As soon as an aircraft leaves the communications range of an aircraft tower, show in gray in Fig. 3 and Fig. 4, the aircraft can no longer be tracked even if there are a number of aircraft in its vicinity. Scenario B and C are much more effective in tracking aircraft than Scenario A, but Scenario B does this at a much higher communication cost than Scenario C.

According to Fig. 6, as the number of aircraft increases the number of signals sent to other craft in Scenario B increases exponentially. This is due to the fact that signals sent in Scenario B must be forwarded by the receiving aircraft until a signal reaches an aircraft control tower. Thus even if no aircraft is in range of a tower, the signals in Scenario B must still propagate throughout the entire set of aircraft. We can see this in Fig. 4 where the areas in red surrounding an aircraft flight path represent that particular aircraft's communication range. Therefore every continuous section of red represents a path that a signal can take. The number of signals for Scenario C, where multicasting and limited hops are considered also increases, specifically when there are 1000 aircraft, but is significantly lower than that compared to Scenario B.

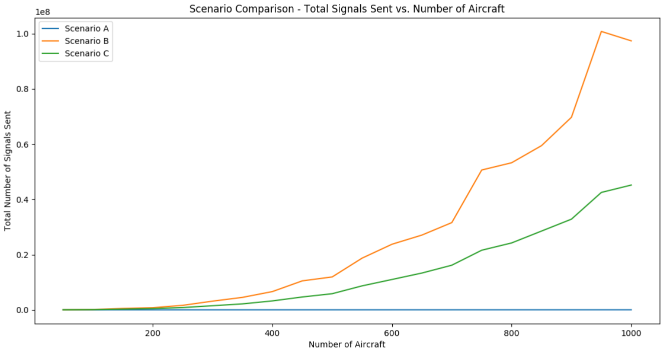

Fig. 6. Comparison of communication overhead for different scenarios

It can be inferred from the simulation results that the performance of Scenario B and Scenario C is much better than that of Scenario A. Scenario B has better location tracking at the cost of communication overhead. Scenario C also performs significantly better that Scenario A, and this technique provides a balance between location detection and communication overhead. The performance of Scenario C increases with number of aircraft, but becomes less responsive after a threshold. However this can be due to the fact that since all aircraft are flying away from their origin towers, it is less likely for a communication chain to form between an aircraft and its origin tower. If more aircraft were to be added to throughout the length of the simulation, a communication chain could form and therefore improve the performance of Scenario B to match that of Scenario C.

Overall the most effective and efficient method to track all aircraft is described in Scenario C i.e., using IoT framework with multicasting and limited number of hops for forwarded messages. Imposing a limit to the propagation of a signal may reduce the effective tracking range but it also limits the amount of resources utilized to send and receive signals from other aircraft, thereby minimizing communication overhead.

VI. CONCLUSION

Being aware of aircraft location at all times in commercial aviation is essential. Although radar based conventional techniques work efficiently to detect and track aircraft, but these methods are not applicable to tracking inter-continental flights, where a significant part of the route is oceanic and has no radar coverage. In this paper we introduce algorithms for location detection using IoT framework for aircraft. The introduced algorithms consider different scenarios, both involving broadcasting and multicasting of location data. The results show that our techniques can effectively track aircraft using IoT based location detection in scenarios where conventional radar mechanism cannot be deployed. Also, the algorithms for multicasting and limited forwarding of messages does reduce the number of messages been exchanged without compromising the tracking percentage. Our future work would focus on other applications that can benefit from the IoT device communication on the aircrafts. Also, clustering aircraft can also be studied to further reduce communication overhead.

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