

# SPAM: Secure & Private Aircraft Management

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## ABSTRACT

With the rising use of aircrafts for operations ranging from disaster-relief to warfare, there is a growing risk of adversarial attacks. Malicious entities often only require the location of the aircraft for these attacks. Current satellite-aircraft communication and tracking protocols put aircrafts at risk if the satellite is compromised, due to computation being done in plaintext. In this work, we present SPAM<sup>1</sup>, a private, secure, and accurate system that allows satellites to efficiently manage and maintain tracking angles for aircraft fleets without learning aircrafts' locations. SPAM is built upon multi-party computation and zero-knowledge proofs to guarantee privacy and high efficiency. While catered towards aircrafts, SPAM's zero-knowledge fleet management can be easily extended to the IoT, with very little overhead.

## CCS CONCEPTS

- Security and privacy → Cryptography;
- Computer systems organization → Embedded and cyber-physical systems; Real-time systems.

## KEYWORDS

Privacy-Preserving Computation, Zero-Knowledge Proofs, Aircraft Privacy, Multi-Party Computation, Two-Party computation

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## 1 INTRODUCTION

Over the past decade, the use of piloted aircrafts, as well as Unmanned Aerial Vehicles (UAVs), has significantly grown. Fleets of remotely controlled vehicles are increasingly used in disaster relief, search and rescue, warfare, and more [18, 21]. The Federal Aviation

<sup>1</sup>The name SPAM (Secure & Private Aircraft Management) is crafted with a dual meaning in mind: signifying the management system's assurance of rendering externally observable aircraft data unintelligible, resembling typical "spam" content.

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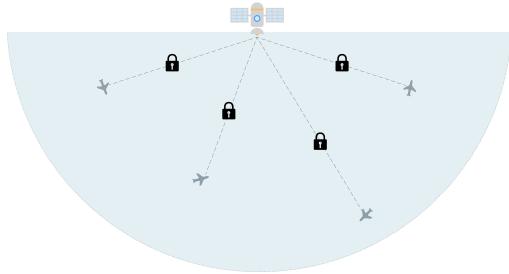
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**Figure 1:** SPAM is an end-to-end aircraft management system that guarantees location privacy to both the aircraft and satellite via scalable Boolean synthesis for secure 2PC and ZKP.

Administration (FAA) of the United States of America (USA) handles approximately 16.5 million flights each year. In addition to the aircrafts, the USA's Department of Defense operates over 11,000 Unmanned Aircraft Systems (UAS) [1]. This includes UAVs, commonly known as "drones". With the increasing number of aircrafts, not just in the USA, but globally, there is also an increased risk of one of these aircrafts becoming the target of an adversarial attack or of "going rogue" (i.e. falling into the hands of enemy forces [6]), and there have already been cases where this is suspected to have happened [13].

Many types of adversarial attacks, such as those using automated weaponry based on GPS tracking, GPS spoofing, jamming attacks, and more, rely on knowledge of an aircraft's location [19]. In addition, satellite-based control systems that require an antenna to be aimed at a remotely controlled aircraft, as well as satellites that provide other types of aircrafts with communication capabilities, can have their transmissions be intercepted [33], thereby revealing the location of the tracked vehicle. For this reason, it is imperative that the computations used to determine the direction that a satellite's antenna faces be done without ultimately revealing the location of the aircraft. This can be accomplished by taking advantage of scalable methods for privacy preserving computation based on synthesis of Boolean logic [24].

Works such as [8, 27] offer solutions aiming to protect the privacy of a drone's location. However, this is done either by simply communicating a temporary location through a secure channel or by obfuscating the location through differential privacy, which would make it infeasible to accurately compute the trajectory from one party to the other. Akkaya et al. [2] focus on private communication of data from an aircraft to a server for machine learning inference

on private data, but do not address concerns for privacy of the aircraft's location. Other methods such as [30] utilize blockchain for secure authentication of drones, but this approach is ineffective for privacy-preserving location management.

Challenges of privacy preservation are further amplified by the communication channels available between aircrafts and satellite. In this work, we assume that aircrafts and satellites communicate using the standardized SATCOM network. SATCOM enables fast aircraft-satellite communication, but lacks encryption below the application layer by default. This puts any communication through SATCOM at risk of eavesdropping attacks, which has been drastically simplified due to the introduction of software defined radios (SDRs) [4]. The solutions require different communication infrastructures or the adoption of secure channels, which increases the overhead and limits the scalability. Scalability is essential, as in many satellite-aircraft communication settings, satellites are actively communicating with many aircrafts at a time for various tasks. One of the most prominent tasks in this domain is the enforcement of certain routes or bounded areas for an aircraft to traverse (e.g. surveillance aircrafts). It is essential to ensure aircraft location privacy in these settings, as eavesdroppers and malicious adversaries that compromise the satellite could mount dangerous attacks if this location is leaked.

In this work, we propose SPAM, the first automated end-to-end solution to private satellite-aircraft localization. SPAM utilizes automated Boolean logic synthesis to build optimal circuits for privacy preserving functions to preserve the secrecy of both aircraft and satellite location. Using a combination of Boolean logic-based two-party computation and zero knowledge proofs, SPAM enables two key tasks in satellite-aircraft localization with strong privacy guarantees: (1) *Movement Tracking*: SPAM enables a satellite to continuously adjust its antenna to maximize communication efficiency without revealing the satellite or aircraft's location and (2) *Location Management*: SPAM enables a satellite to monitor aircrafts within its network and ensure that they are staying within certain bounds, without learning the exact locations of the aircrafts.

To the best of our knowledge, we propose the first method that securely verifies the correct angle of a satellite's antenna for aircraft communication. Further, SPAM is the first work to allow satellites to enforce location bounds for aircrafts in their networks, without revealing the exact location of the aircrafts. SPAM not only elegantly solves these problems with very little overhead, but also defends against eavesdropping attacks on SATCOM networks due to the use of privacy-preserving computation.

In summary, our contributions are as follows.

- Introduction of SPAM, the first automated end-to-end framework for privately tracking and managing aircrafts, without revealing any location information.
- Enabling unintelligible tracking of location (without recompute) by introducing new 2PC-based methods for further private tracking of aircraft trajectories.
- Utilizing scalable Boolean logic synthesis to design novel circuits compatible with interactive zero-knowledge proof protocols which enforces spatial bounds for aircrafts.
- Extensive evaluations of SPAM highlight its performance at scale, while providing privacy to all parties involved.

## 2 PRELIMINARIES

With increasing data-driven decision making and information sharing, there has been a growing need for privacy preserving computation to protect our sensitive data. A variety of solutions have emerged over the years, with one efficient and robust choice being multi-party computation (MPC), which allows for joint computation on private data by multiple parties while achieving provable privacy and accuracy.

### 2.1 Multi-Party Computation

In MPC schemes,  $n$  parties, each holding their own private inputs denoted as  $d_1, d_2, \dots, d_n$ , perform joint computation of a public function,  $F(d_1, d_2, \dots, d_n)$ , such that only the output of this function is revealed while the each party's input remains private. There are generally two settings of MPC - namely *semi-honest* and *malicious* settings. In semi-honest settings, parties may gather information passively without straying from the designated protocol. In malicious settings, parties are able to actively pursue information both passively, as with the semi-honest setting, but also by deviating from the designated protocol to gain more information [10]. In this work, we utilize two-party computation, a subset of multi-party computation.

**2.1.1 Two-Party Computation.** Two-party computation (2PC) was first introduced by Andrew Yao in 1986 and was later extended by Goldreich, Micali, and Wigderson to MPC [12, 32]. 2PC often relies on the use of garbled circuits, a topic first introduced by Yao but further formalized by Beaver et al. [5]. Garbled circuit based evaluation involves two parties, namely a *garbler* and an *evaluator*. The garbler's role is in generating a circuit that describes an underlying function to be computed with both parties' inputs. The evaluator receives this circuit from the garbler and by using Oblivious Transfer [20], the evaluator is able to garble its own input with the help of the garbler, without the garbler learning the evaluator's input. The function is then evaluated, which results in both parties obtaining the function's output without revealing any information about each other's inputs in addition to what can be inferred from the output itself. Beaver-Micali-Rogaway (BMR) is one method of implementing garbled circuits by utilizing generalized secure protocols for 2PC to compute the garbled circuit [5].

### 2.2 Zero-Knowledge Proofs

Zero-Knowledge Proofs (ZKPs) are a two-party cryptographic primitive between two parties: prover  $\mathcal{P}$  and verifier  $\mathcal{V}$ . ZKPs enables  $\mathcal{P}$  to prove that the the evaluation of a computation  $C$  on a private value  $w$ , called the witness, is valid without revealing anything about  $w$ . In standard ZKP schemes,  $\mathcal{P}$  convinces  $\mathcal{V}$  that  $w$  is a valid input such that  $y = C(x, w)$ , where  $x$  and  $y$  are public inputs and outputs, respectively [11]. Interactive ZKP schemes require many rounds of interaction between  $\mathcal{P}$  and  $\mathcal{V}$  to successfully build a ZKP. Non-interactive ZKPs (NIZKs) allow for proof generation to be done in one step, but often require a rigorous trusted setup process per computation  $C$ . While NIZKs have smaller proof size and faster verification, they benefit from *publicly-verifiable* proofs, meaning that any  $\mathcal{V}$  can verify the proof.

Conversely, interactive ZKPs have larger proofs and are *designated verifier*, meaning that only the verifier interacting with  $\mathcal{P}$  can verify the proof, however do not have a trusted setup process. One of the main advantages of interactive proofs is the reduced prover complexity when compared to NIZKs. This becomes especially suitable when working with resource-constrained devices, such as those in IoT settings, which we discuss in detail in section 5. While the *designated verifier* constraint can be viewed as a drawback, we will explain that this is actually suitable for our system, and far outweighs the drawback of having a rigorous trusted setup process. In this work, we employ the Wolverine protocol [17], a state-of-the-art interactive ZKP system that is notably efficient in terms of execution time, memory demands, and data transfer for  $\mathcal{P}$ . Within this protocol, the witness  $w$  is verified using information-theoretic message authentication codes (IT-MACs). Computations in Wolverine are structured as either arithmetic or Boolean circuits, and are collaboratively evaluated by  $\mathcal{P}$  and  $\mathcal{V}$ . Upon completion,  $\mathcal{P}$  reveals the output to demonstrate the validity of the proof, which in our case is proving that the evaluated output matches a pre-existing public output.

### 3 RELATED WORK

Works such as PPCA [27] recognize the threats of location leakage to adversaries. With increasing investments from stakeholders such as Google and Amazon, there are more drones being used for autonomous delivery each year. The authors claim to be the first ones to develop an improved collision detection system that maintains the privacy of the drone locations rather than having each UAV openly broadcasting its location - the current norm. They do so by having UAVs share temporary locations through secure wireless connections to nearby drones that have a risk of colliding with each other.

In Hide and Seek [8], the authors show that Critical Infrastructure operators are able to preserve drone privacy while detecting drones violating no-fly zone designations. They provide DiPrID, a framework which uses differential privacy to improve drone location privacy. They also propose ICARUS, which provides a solution for detecting unauthorized drones within no-fly zones.

The authors of [25] outline the lack of mechanisms for the privacy preservation of drone locations but do not provide implementation to fill this gap. [3, 26] further demonstrate the need for location privacy by showcasing various attacks on drones, such as jamming and GPS spoofing, that rely on knowing a drone's location.

Works such as [2, 9] discuss the growing issues of drones capturing sensitive data and provide frameworks for enabling privacy-preserving transmission of data captured by drones, such as video recordings. However, they do not discuss the privacy of the drone itself.

Research interest in efficient privacy preserving computation has drastically increased in recent years. Developments in the field have allowed for advancements in a variety of private computing applications such as machine learning model inference on sensitive data, credit scoring, identity verification, and more [14, 17, 22]. A number of methods are used, such as multiparty computation and homomorphic encryption, which allow for secure computation on private data. Alongside this, zero-knowledge proofs are an emerging

technology that allow users to prove attributes about their data, without revealing anything about their data [11].

## 4 METHODOLOGY

Many aircrafts, including UAS or drones, are often remotely controlled through satellite systems, which aim an antenna towards them to achieve efficient transmission. Naively, this can be accomplished through the aircraft communicating its location to the satellite. However, this approach exposes the aircraft's location to the satellite, introducing vulnerabilities if the satellite is compromised by adversaries.

SPAM provides secure computation of the trajectory from a spacecraft to an aircraft through 2PC and a fleet management system built on zero-knowledge proofs, all without compromising the location of either party. We represent the trajectory using a *trajectory unit vector*, which is simply a vector of magnitude one that defines the direction from the satellite to the aircraft in three dimensional space.

### 4.1 Threat Model(s)

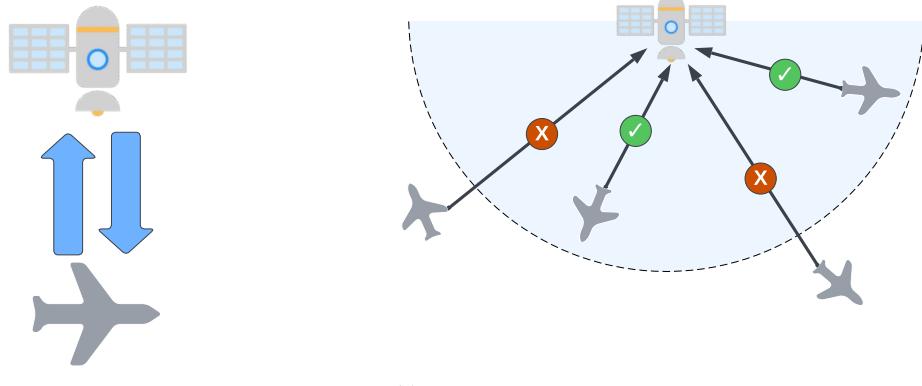
SPAM aims to protect the privacy of the aircraft's location from the satellite, as leaking this could make the aircraft susceptible to attacks from adversaries. Alongside this, we would like to leak as little information as possible about the satellite to the aircraft, which is why two-party computation and zero knowledge proofs are employed in SPAM. In our setting, we assume that both parties are *semi-honest*, meaning that they will follow the given protocol, but try to learn as much information as possible with the data in hand. While not the main contribution of this work, we also consider the threat of a malicious satellite that may deviate from the protocol.

### 4.2 SPAM Overview

SPAM consists of two core functionalities: movement tracking and location management. The main task of SPAM's movement tracking is privately updating the angle of a satellite's antenna to ensure that it is pointing at the aircraft, without revealing the exact location of the aircraft. The main task of SPAM's location management is to generate and verify proofs in which aircrafts attest to the satellite that they are bound-compliant. We note that we use scalable Boolean logic synthesis [24, 29] to optimize our 2PC and ZKP circuits, ensuring state-of-the-art performance.

**4.2.1 Movement Tracking.** An aircraft or drone is equipped with a communication system that requires a satellite connection. In order to transmit information most efficiently between the aircraft and the satellite, an antenna on the satellite must point itself at the aircraft's changing location. We denote the aircraft by  $p$ , the satellite by  $s$ , and the locations of the satellite and the aircraft by  $(x_s, y_s, z_s)$  and  $(x_a, y_a, z_a)$ , respectively. If the satellite's location is public, we are able to simply have the aircraft perform the computation of the satellite's trajectory unit vector and send the computed vector to the satellite. This fulfills all of privacy requirements for the aircraft without the need for expensive private computation. This simple algorithm is described in Algorithm 1.

However, under SPAM's stricter privacy constraints, we assume that both of the aircraft's and satellite's locations must remain



(a) **Trajectory Computations:** The aircraft and satellite jointly compute the unit vector describing the desired trajectory for the satellite's antenna using Two-Party Computation.

(b) **Range Checks:** Aircrafts periodically send a ZKP to prove to the satellite that they are still within range.

Figure 2: High Level Overview of SPAM.

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**Algorithm 1** Plain-text Trajectory Unit Vector Calculation
 

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**Input:**

Satellite location (sent to aircraft):  $(x_s, y_s, z_s)$   
 aircraft location (known by aircraft):  $(x_a, y_a, z_a)$

**Computed:**

Vector  $v = (x_v = x_a - x_s, y_v = y_a - y_s, z_v = z_a - z_s)$

Magnitude  $m = \sqrt{x_v^2 + y_v^2 + z_v^2}$

Unit vector  $a = \left( \frac{x_v}{m}, \frac{y_v}{m}, \frac{z_v}{m} \right)$

**Send the Unit vector to the satellite.**

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private. We rely on 2PC to securely compute the trajectory. In this more secure setting, we perform the same computations as we have in Algorithm 1 but using secure protocols. This new formulation is described in Algorithm 2. We build our computation using semi-honest and malicious secure two-party methods based on oblivious transfer (OT). For the semi-honest threat model, we utilize the Semi [15] protocol, which utilizes OT and secret sharing over a large prime field to support semi-honest computation. For the malicious threat model, we use the MASCOT [16] protocol, which builds off of Semi. MASCOT primarily adds MAC keys and OT correlation and consistency checks to Semi to support malicious parties. The utilization of these methods enable SPAM to securely compute the trajectory unit vector with the aircraft's and satellite's locations as private inputs. After secure computation, the resulting trajectory unit vector is only revealed to the satellite. This is done to protect the satellite's location, as the aircraft could triangulate the satellite's location if more than one unit trajectory vector was learned during movement.

**4.2.2 Location Management.** Satellites are often in communication with many aircrafts at a given time. In tasks, such as surveillance, a satellite would like to enforce that the aircrafts are staying within these bounds. However, the aircraft wants to ensure that their location within these bounds is not revealed, in the event of the satellite being compromised. SPAM enables this with a provably private

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**Algorithm 2** Private Trajectory Unit Vector Calculation
 

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Satellite location:  $(x_s, y_s, z_s)$

Aircraft location:  $(x_a, y_a, z_a)$

*Party1*  $\leftarrow$  Satellite

*Party2*  $\leftarrow$  aircraft

**Computed:**

$f \leftarrow \text{gen\_garble\_circuit}(\text{get\_trajectory}(a, b))$

$g_1 \leftarrow \text{garble}(x_s, y_s, z_s)$

$g_2 \leftarrow \text{garble}(x_a, y_a, z_a)$

$\text{reveal\_to\_party\_1}(f(g_1, g_2))$

**Note:** `get_trajectory()` is the function described by Algorithm 1

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location management scheme. SPAM's location management is built upon ZKPs, which enables the aircrafts to prove that they are within bounds that are predetermined and updated by the satellite, while ensuring that the specific locations of the aircrafts are not revealed in the event of the satellite being compromised.

The bounds that the satellite enforces are established in the form  $[(x_{min}, x_{max}), (y_{min}, y_{max}), (z_{min}, z_{max})]$ . We design an efficient Boolean circuit for the  $\geq$  and  $\leq$  comparisons, based on fast custom multiplexers, that is compatible with the Wolverine protocol that returns a single bit. These circuits are used to compare the aircraft's current location  $(x_a, y_a, z_a)$  with the satellites' enforced bounds in zero-knowledge. As computation in Wolverine is represented as Boolean circuits, we aim to take advantage of this by performing primarily bitwise operations. The high-level algorithm we employ can be seen in algorithm 3. As Wolverine has optimized implementations of zero-knowledge AND gates, SPAM's location management requires very little overhead.

### 4.3 Implementation Details

While there are many coordinate systems for representing location in 3D space, we chose to evaluate on the Cartesian coordinate system. Other methods, such as the use of polar coordinates, often rely

**Algorithm 3** Check if aircraft is in bounds

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Aircraft  $\leftarrow$  Prover
Satellite  $\leftarrow$  Verifier
Input:
Bounds:  $[(x_{min}, x_{max}), (y_{min}, y_{max}), (z_{min}, z_{max})]$ 
Aircraft location (known by aircraft):  $(x_a, y_a, z_a)$ 
ZK Circuit:
Bit  $x = x_a.geq(x_{min}) \text{ AND } x_a.leq(x_{max})$ 
Bit  $y = y_a.geq(y_{min}) \text{ AND } y_a.leq(y_{max})$ 
Bit  $z = z_a.geq(z_{min}) \text{ AND } z_a.leq(z_{max})$ 
Bit  $valid = x \text{ AND } y \text{ AND } z$ 
Return valid

```

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on trigonometric functions to determine the distance and direction between points in space. These functions are often more expensive to compute, particularly in the realm of privacy-preserving computing.

SPAM’s 2PC location tracking implementation is built using MP-SPDZ [15]. MP-SPDZ is a user-friendly library that allows for implementation of 2PC while leveraging a variety of protocols to use in the backend. This enables benchmarking of different contexts, such as in semi-honest and malicious settings. We use SPAM’s zero-knowledge location management is built using the Wolverine [31] protocol, an efficient interactive ZKP protocol that boasts highly scalable communication and performance. For both applications, we utilize state-of-the-art scalable Boolean logic synthesis tools [24, 29] to design low-level, optimized representations of our computation.

## 5 EVALUATION AND DISCUSSION

### 5.1 Setup

The end-to-end SPAM framework is implemented in C++ and the MP-SPDZ domain specific language. We use the EMP-Toolkit [29] for implementation of zero-knowledge proofs. We run all experiments on a 128GB RAM, AMD Ryzen 3990X CPU desktop.

### 5.2 Results

We benchmark SPAM’s capabilities over several bitwidths ranging from 128 to 8 bits. We note that we do not perform separate experiments for the semi-honest and malicious threat model for the location management task as Wolverine is designed to be maliciously secure, however supports semi-honest parties. The results can be seen in Tables 1 and 2. As can be seen in both applications, the communication is not affected by the bitwidths. This is due to the fact that all the specific protocols - Semi, MASCOT, and Wolverine - that are used in SPAM are designed such that communication grows with respect to the size of the computation/circuit. Due to the lean, optimized algorithms we design for SPAM, the communication cost is negligible in the semi-honest movement tracking and location management tasks. We see a significant increase in communication cost and runtime in the malicious location management setting, as MASCOT introduce OT correlation checks and MAC generation schemes to ensure that the protocol is completely soundly.

In semi-honest movement tracking and location management, SPAM boasts very low runtime, making SPAM a real-time solution

Bitwidth	Semi-Honest		Malicious	
	Runtime (s)	Comm. (MB)	Runtime (s)	Comm. (MB)
128	0.13	0.75	3.44	168.40
100	0.09	0.75	3.18	168.40
64	0.08	0.75	3.13	168.40
32	0.08	0.75	3.12	168.40
16	0.08	0.75	2.96	168.40
8	0.06	0.75	2.95	168.40

**Table 1: Evaluation of SPAM’s Movement Tracking**

Bitwidth	Prover ( $\mathcal{P}$ )		Verifier ( $\mathcal{V}$ )	
	Runtime (ms)	Comm. (kB)	Runtime (ms)	Comm. (kB)
128	53.87	84.54	44.88	105.12
100	33.39	84.54	34.45	105.12
64	24.79	84.54	23.32	105.12
32	11.5	84.54	10.14	105.12
16	6.71	84.54	6.92	105.12
8	5.96	84.54	6.08	105.12

**Table 2: Evaluation of SPAM’s Location Management**

for private aircraft management. While the malicious movement tracking setting leads to much higher runtime, this is a common pitfall of the malicious threat model. Due to the significantly increased amount of computation that needs to be done to ensure that a malicious party does not break the protocol, this increased runtime is unavoidable. We provide the measurements of runtime for several bitwidths, from 128 bits to 8 bits. This is done to show how SPAM overhead changes based on the amount of precision that is necessary to successfully locate or prove the location of an aircraft. Based on the bandwidth and computational power that is available at a given time, the bitwidth can be adjusted to reduce the computational overhead or satellite-aircraft interaction time.

The presented results highlight the communication and computational efficiency that SPAM achieves by utilizing novel techniques combined with state-of-the-art privacy-preserving protocols. Unlike most privacy-preserving approaches, SPAM is not limited by scale, as the circuit sizes and the number of parties per computation stay constant. The only minor bottleneck is communication, which only becomes a problem if the network, SATCOM in our case, has limited bandwidth. Overall, the results show that SPAM is a real-time solution to private aircraft management that can scale to real-world applications.

### 5.3 Extending SPAM

As a brief aside, we want to discuss the extension of SPAM into the IoT - particularly the zero-knowledge location management aspect. Oftentimes, edge devices have computational and bandwidth constraints, which makes it challenging to implement privacy-preserving solutions in the IoT. Due to the lightweight communication and computational overhead that we show for SPAM, we believe that this work can be easily extended to the IoT and provide a secure solution towards edge devices proving attributes of their collected data. In SPAM, we have aircrafts proving that their current location is within certain pre-determined bounds using ZKP

techniques. There are many works that demonstrate the feasibility of ZKP-based systems for IoT devices [7, 23, 28]. It is therefore expected that the ZKP techniques employed in SPAM can be extended to different sensor-based IoTs. For instance, users that utilize biomedical IoT edge devices can adopt the SPAM approach to prove that their health vitals (e.g. heart rate) are within a certain "safe" range. As health data is often sensitive, the user would prefer that this data stays private, unless their vitals are deemed to be in an unsafe range. While this is just an example, it is clear to see that SPAM's approach towards aircraft location management can be modified to span many domains within the IoT.

## 6 CONCLUSION

In this work, we presented SPAM, a privacy preserving framework for optimizing transmission efficiency and aircraft management. By leveraging methods for secure two-party computation, SPAM preserves the privacy of each party's location while enabling a satellite to maximize its communication throughput by securely computing the optimal trajectory for its antennas to take. SPAM also utilizes zero-knowledge proof techniques to provide a monitoring system that enables a satellite to determine if an aircraft's location falls within a predetermined range without revealing the exact location of the aircraft. Automated Boolean logic synthesis is utilized for representing computation to ensure state-of-the-art runtime and communication for our given application. While many standard methods of satellite communication provide little privacy preservation, SPAM implements an automated end-to-end system for protection against both semi-honest and malicious adversaries, as well as security against eavesdropping attacks, with little overhead.

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