Blockchain Enabled Secure Authentication for Unmanned Aircraft Systems

Yongxin Liu^{1*}, Jian Wang^{2*}, Yingjie Chen³, Shuteng Niu⁴, Zhihan Lv³, Lei Wu¹, Dahai Liu², Houbing Song²

¹Auburn University at Montgomery, AL 36117 USA

²Embry-Riddle Aeronautical University, Daytona Beach, FL 32114 USA

³Qingdao University, Qingdao, Shandong 266071 China

⁴Bowling Green State University, Bowling Green, OH 43403 USA

¹{yliu19,lwu}@aum.edu, ²wangj1@my.erau.edu, dahai.liu@erau.edu, h.song@ieee.org

³2018207163@qdu.edu.cn, lvzhihan@gmail.com, ⁴sniu@bgsu.edu

Abstract—The integration of air and ground smart vehicles is becoming a new paradigm of future transportation. A decent number of smart unmanned vehicles or UAS will be sharing the national airspace for various purposes, such as express delivery, surveillance, etc. However, the proliferation of UAS also brings challenges considering the safe integration of them into the current Air Traffic Management (ATM) systems. Especially when the current Automatic Dependent Surveillance Broadcasting (ADS-B) systems do not have message authentication mechanisms, it can not distinguish whether an authorized UAS is using the corresponding airspace. In this paper, we aim to address these practical challenges in two folds. We first use blockchain to provide a secure authentication platform for flight plan approval and sharing between the existing ATM facilities. We then use the fountain code to encode the authentication payloads and adapt them into the de facto communication protocol of ATM. This maintains backward compatibility and ensures the verification success rate under the noisy broadcasting channel. We simulate the realistic wireless communication scenarios and theoretically prove that our proposed authentication framework is with low latency and highly compatible with existing ATM communication

I. Introduction

The emerging Unmanned Aircraft System stimulates the development of a new paradigm of transportation, the integration of different modes of autonomous and smart vehicles to facilitate the agile mobility of people and cargo between places [1]-[3]. In this context, Advanced Air Mobility (AAM) aims to develop air transportation systems that move people and cargo between places previously not served or underserved by aviation using revolutionary new aircraft, such as smart UAS [4], [5]. The principal requirement for AAM is the coexist of UAS and regular aircraft within the national airspace under a unified and coordinated management framework [6]-[8]. However, this requirement brings challenges to the current Air Traffic Management (ATM) systems. Currently, several obstacles impede the integration of UAS into the national airspace, and the most difficult ones are real-time verification and airspace usage authentication [9]-[11]. These criteria require the UAS to broadcast its identity to ATM facilities in a verifiable and trustworthy way.

In regular scenarios, each operational aircraft uses an ADS-B transponder at 1090MHz to broadcast its ID, and other critical flight information to the ATC facilities [12], [13] while a Remote ID Broadcast Module [14], [15] is required for UAS. In these solutions, all communication entities within the current solution broadcast the critical information using plain text without cryptographic features. Consequently, ATM systems are still vulnerable to cyber attacks. For example, a malicious adversary can deliberately broadcast a high volume of fake data packets to mislead and interrupt the normal operations of ATC. In addition, the ADS-B protocol has become a de facto standard with corresponding transponders installed on nearly every aircraft. It is impossible to upgrade them in a short time for secure authentication features. System upgrades in the aviation industry need to be taken with sufficient backward compatibility.

Non-cryptographic solutions have been proposed to facilitate the existing ATM systems with identity verification capability [16]–[18]. The key idea of these approaches is to derive the protocol-agnostic physical layer features from the raw signals for pattern recognition, and transmitter identification [19]-[21]. However, on the one hand, the physical layer features of raw signals can change drastically under different conditions (e.g., interference, weather, or antenna characteristics), making it difficult to get a widely acceptable wireless transmitter identification model. On the other hand, although cryptographic identity verification approaches are more reliable, the communication channel bandwidth between UAS and ATM facilities is limited. Therefore, special mechanisms are needed to ensure the successful delivery of authentication information while maintaining backward compatibility with the existing ATM infrastructures.

In this paper, we propose a secure framework for the safe integration of UAS into the national airspace. We first propose a blockchain enabled framework for the authentication of flight plans and exchanging secret keys between UAS and ATM infrastructures. We then provide an enhanced ADS-B protocol using fountain code [22], [23] for the reliable transmission of authentication information in capacity-limited wireless channels. Our contributions are as follows:

- We provide a blockchain based framework for the review and authentication of flight plans between UAS and existing ATM infrastructure, which is reliable and robust to single-point failure under cyber attacks.
- We provide a backward compatible and enhanced ADS-B protocol for aviation communication. The protocol increases the trustworthiness and reliability of communication between UAS and ATM.
- We theoretically prove that our proposed authentication framework is highly compatible with the de facto ATM communication protocol.

Our research offers a solution for cyber defense in air and ground smart vehicle networks. This solution maintains the best backward compatibility with the existing air traffic management facilities and can be extended to protect the communication channel of manned aircraft. The remainder of this paper is organized as follows: A literature review of related works is presented in Section II. The methodology in Section III. Performance evaluation is presented in Section IV with conclusions in Section V.

II. RELATED WORK

A. Blockchain in Cyber Physical Systems

Blockchain is a specific kind of decentralized and distributed database that utilizes cryptography algorithms and consensus mechanisms to prevent information from being modified maliciously [24], [25]. The most elegant feature of the blockchain is information integrity, in which no one can modify the data without controlling greater than 50% of computational resources among all peers [26], [27]. Blockchain has been adapted to many Cyber-Physical Systems for secure data storage [28]. For example, in [29], a scalable framework is proposed to manage the accessibility of computational resources using Blockchain. Their approach introduces a Private Blockchain Network in the Cloud as well as one Management Hub. In [30], a Blockchain-enabled hierarchical Cloud architecture for CPS is proposed, and the Blockchain is deployed as a secure information exchange media within the service provider and consumers. Blockchain can also be used as a secure middleware for network routing and authentication [31]–[33].

B. Non-cryptographic Identity Verification in Air Traffic Surveillance Systems

ATM systems are becoming a crucial infrastructure for VANETs and UAS. In this domain, the non-cryptographic identity verification of UAS and manned aircraft is attracting attentions. Authors in [34] used the instantaneous phase varying pattern of signals as a distinctive feature for aircraft identification. Phase patterns can be applied to low-cost equipment, as in [35] and [36], the authors extract the phase patterns in each ADS-B message and use a Deep Neural Network (DNN) model to identify the genius ones. However, a common problem of these research is that the identification model is not robust to the varying wireless channels and RF front-ends. This

motivates us to provide a more robust solution using proactive fingerprint embeddeding with backward compatibility.

III. METHODOLOGY

This section will provide an overview of the system model, followed by the blockchain infrastructure and procedures for secure authentication of UAS with the existing ATM facilities. We will then introduce our modification of the enhanced ADS-B protocol for the identity verification of UAS in real-time.

A. System Model

The system diagram of our proposed solution is in Figure 1. As depicted, we suppose that all ATM facilities (including ATC facilities and weather observation stations) are connected as nodes in a private blockchain network. In this ATM blockchain network, vital information such as airspace availability, weather, flight plans, etc., can be shared and stored securely. We also define that UAS users are supposed to submit their flight plans via regular civilian communication media, such as cellular networks. The submitted flight plans are assessed and authorized by smart contracts. Once a flight plan is approved, the en-route authentication credentials (tokens) will be delivered to the UAS and are utilized to generate the enhanced ADS-B packets.

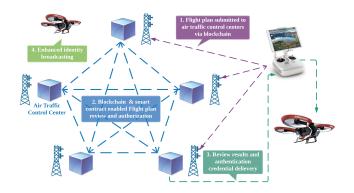


Fig. 1. Blockchain authentication framework for UAS

B. Blockchain for Secure Flight Plan Assessment

We utilize blockchain and smart contracts to make flight plan assessment transparent and secure. In other words, the malicious needs to compromise at least 51% of the nodes in the blockchain network to malfunction the assessment process. The procedures of flight plan submission and assessment procedure of flight plans are as follows:

- Step 1: UAS users submit flight plans with digital signatures to the ATC blockchain network via ground control stations. Flight plans will be broadcast to all nodes in the ATM blockchain network. In general, a flight plan contains waypoints, estimated times of arrival, and the UAS registration number.
- **Step** 2: Once a flight plan is broadcast, the smart contract will assess it with the newest regulations and information.

If the smart contract approves a flight plan, an appropriate node in the ATM blockchain will be selected to generate an authentication credential for this flight plan. We first generate a list of the top ten candidates using the metric as:

$$s = \frac{1}{D+L+1} \tag{1}$$

where L is the averaged latency of authentication credentials generation within the past 24 hrs, and D is the distance between the take-off point and the related nodes within the air space. We then randomly select one out of ten to generate the authentication credential.

Step 3: The authentication credential of a flight plan is composed of: i) a temporal symmetric key (SK_p) . ii) a hash digest for the flight plan (ID_{fp}) generated by the smart contract. iii) a challenge string. iv) the digital certificate of the flight plan signed by the issuance facility (ID_{if}) . iv) The LT Code message generation matrix M_{LT} [37]:

$$M_{LT} = \begin{bmatrix} 1 & 0 & 0 & \cdots \\ \vdots & \vdots & \vdots & \dots \\ 0 & 1 & 1 & \cdots \end{bmatrix}_{K \times N}$$
 (2)

where M_{LT} is the message generation matrix of LT code, a practical implementation of fountain code. The message generation matrix contains only zeros and ones, M_{LT} needs to have full rank. It actually represents the Tanner Graph of the LT code encoder. LT code is the practical implementation of fountain code.

Step 4: The authentication credential of a flight plan is first broadcast within the ATM blockchain network. Then it's encrypted by the public key $(PubK_U)$ of the UAS user and sent back to the ground control station of UAS.

Given these steps, a UAS user can verify that a trustworthy entity formally approves the flight plan. Meanwhile, a UAS will be able to generate its authentication information during its flight. In this work, we assume that the UAS can always maintain a reliable Internet connection in the preflight stage. We believe that temporal symmetric encryption is more appropriate to secure the en-route communication between UAS and ATC facilities with low overhead.

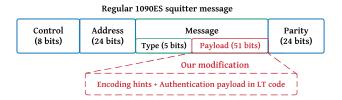


Fig. 2. Data block of ADS-B message and our modification

C. Enhanced ADS-B Protocol for Reliable Broadcast Authentication

ADS-B is the standard for ATC and ATM. In a Mode S transponder with Extended Squitter, a standard data packet contains only 112 bits and does not contain any authentication payload [12]. Therefore, some modifications are needed. Specifically, we propose a new message category termed as authentication message. According to the data blocks of ADS-B message in Figure 2, we can have 51 bits available in the periodically broadcast 1090ES squitter message. Therefore, the size of the encoded symbols for LT code needs to be less than 51 bits because we also need to reserve bits to indicate how we generate the symbol. These hints are termed as *encoding hints* in Figure 2. Given that the length of the raw authentication payload is M, we need to divide the raw authentication message into K equal-sized symbols (C_1, \dots, C_K) , and the size of each symbol (L_C) has to satisfy:

$$L_C < 51 - L_h \tag{3}$$

where L_h is the size of the encoding hints. In our solution, an encoding hint indicates the column vector in M_{LT} that is used to generate an encoded symbol. We also define that the number of column in M_{LT} needs to satisfy:

$$N > r_0 \cdot \frac{M}{L_C} \tag{4}$$

where $r_0(r_0 > 1)$ is the redundancy coefficient and M is the size of the authentication payload before encoding. It means that during the transmission of a complete authentication payload, every symbol is generated using a different sub graph.

To avoid reusing columns in the message generation matrix, we have the following constraint:

$$51 - \left\lceil Log_2[N] \right\rceil \ge L_C \tag{5}$$

where $\lceil Log_2[N] \rceil$ is the length of the encoding hints, M is the size of authentication payload, L_C is the size of encoded symbols. Therefore, the configuration of parameters can be categorized into a constrained optimization problem.



Fig. 3. En-route authentication

Once a UAS takes off, it is supposed to broadcast the authentication payload using LT Code periodically. The authentication payload contains the certificate of the current flight plan (ID_{fp}) plus a response to the cryptographic challenge. The authentication procedure is depicted in Figure 3, also as follows:

Step 1: If the LT Code message generation matrix is with K rows and N columns as in (2). The message generation procedure resembles matrix multiplication, but we use binary XOR to replace the binary addition during calculation:

$$[E_1, \cdots, E_N] = [C_1, \cdots, C_K] \times \mathbf{M_{LT}}$$
 (6)

where C_1, \cdots, C_K are segments of the raw message (the authentication payload). E_1, \cdots, E_N are encoded authentication messages to broadcast. In the context of fountain code, E_1, \cdots, E_N are termed as droplets.

Step 2: Once a ATC facility intercepts $N_L(M/L_C)$ authentication messages, it will then try to decode and reconstruct the authentication payload:

$$[C_1, \cdots, C_K] = [E_1, \cdots, E_N] \times M_{LT}^{-1}$$
 (7)

where M_{LT}^{-1} is the inverse of M_{LT} . We can also use Belief Propagation algorithm to reconstruct the payload [37]. The reconstructed authentication payload will be broadcast and sent to the smart contract.

Step 3: The smart contract can broadcast the authentication result and periodically change the challenge string via ADS-B interrogation protocol [38].

For UAS with higher computational capabilities, we can further require the UAS to digitally sign its response to the challenge string. In which it will be computationally impossible to generate fake authentication credentials.

IV. EVALUATION AND DISCUSSION

In this section, we will discuss the attack surface of the framework and evaluate the performance of the en-route authentication payload encoding scheme.

A. Security Analysis

We discuss the possible attacks in two stages: preflight and en-route, as in Table I. The malicious attackers need to get access to the ATM blockchain or gain the private keys of UAS and its owners to compromise the security mechanism. There are many ways we can prevent malicious attackers from accessing the ATM blockchain, such as multifactor authentication. Therefore, we believe this authentication framework is sufficiently secure.

B. Performance Evaluation of the Encoding scheme

For ADS-B systems, the worst-case Packet Loss Rate (PLR) with distance has been proposed in [39] as:

$$y = 65.366 + 0.020319 \times distance[km] \tag{8}$$

Therefore, we only need to set the range of PLR from 65% (less than 1 km) to 95% (1485 km). We initially set the size of symbols to be 16 bits and compare the average number of data packets needed to reconstruct the authentication payload under different PLR is given in Figure 4. The number of encoded packets increases with two factors: i) the size of the raw authentication payload. ii) the packet loss rate of the

TABLE I
THE POSSIBLE MALICIOUS ATTACKS AND SUCCESS CRITERIA IN OUR
FRAMEWORK

Stage	Malicious attacks	Attack success criteria
Preflight	Submiting falsified flight plans.	The malicious gains the private key of UAS.
	Malfunctioning flight plan assessment functionality.	The malicious controls at least one third of the nodes in the ATM blockchain.
	Generating fake flight approval and authentication credentials.	The malicious gets the private keys of ATM facilities.
	Intercepting flight plans approvals and authentication credentials.	The malicious gets the private key of UAS or gain the assessibility of ATM blockchain.
En-Route	Transmitting fake authentication messages.	The malicious gets the authentication credentials or will be impossible if the challenge-response requires digital signature.
	Bypassing the en-route authentication mechanism	The malicious needs to control at least one third of the nodes in the ATM blockchain.
	Recording and re-transmit data packets to create ghost aircraft.	Can temporally succeed but will be detected once the challenge string is updated and contains a sequence number.
	Compromising a few nodes to inject fake en-route information to the ATM blockchain.	Depends on how many nodes an attacker controls. Since ADS-B messages can be picked up by multiple recipients.

wireless channel. We also compare the minimal value of r_0 under different PLR in Figure 4. The minimal value is defined as:

$$r_0^* = \frac{N_{PLR}}{N_0}$$
 (9)

where N_{PLR} is the average number of non-repeated encoded packets needed to reconstruct the authentication payload properly. N_0 is the minimal number of encoded packets needed to reconstruct the payload where PLR = 0. As in Figure 4, r_0^* grows exponentially with the increase of PLR and does not seem to be affected by the size of raw payloads.

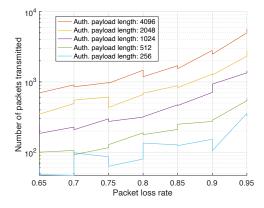


Fig. 4. Average number of packets needed to reconstruct authentication payloads with symbol size being 16 bits.

If we limit the range of UAS operation to 100 km, the maximum PLR becomes 68%. Then we can simulate the performance of the authentication encoding scenario. We focus

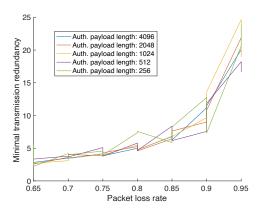


Fig. 5. Transmission redundancy with different PLR and symbol size being 16 bits

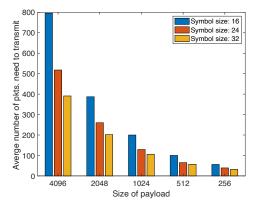


Fig. 6. The average number of packets needed to properly deliver authentication payloads (the range of communication is less than 100 km).

on the minimal redundancy and the average number of packets we need to transmit to deliver the authentication payload properly. As depicted in Figure 6 and 7, large authentication payloads require more data packets to deliver properly, but the average transmission redundancy maintains relatively stable. In the meantime, we can reduce the packets needed to deliver the payload. The redundancy of transmission is relatively stable.

C. Practical Configuration and Adaptation

Suppose that we want to deploy this authentication framework into the real ADS-B transponders for UAS and regular aircraft. We can configure the size of the authentication payload to be 1024 bits and the symbol size to be 32 bits. In this way, authentication messages can be delivered and reconstructed within 120 ADS-B packets (less than one minute). As in Figure 7, the redundancy for transmission needs to be around 3.25. Therefore, we should provide $\lceil log_2(1024 \times 3.25)/32 \rceil = 7$ bits to store the encoding hints L_h . As we have $51 \ bits > 32 + 7 = 39(bits)$. Consequently, the de-facto ADS-B protocol is capable of carrying on the proposed authentication framework. Even if we use a 2048-bit authentication payload, we only need $\lceil log_2(2048 \times 3.25)/32 \rceil =$

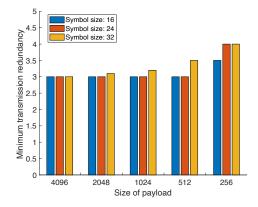


Fig. 7. The average redundancy of data transmission to properly deliver authentication payloads (the range of communication is less than 100 km).

8 bits to store the decoding hints. We still have 43 bits to store the authentication symbols. Therefore, we believe that this authentication payload encoding algorithm is fully compatible with the de facto ADS-B protocol in air traffic control facilities.

V. CONCLUSION

In this paper, we propose a secure framework for the safe integration of UAS into the national airspace. We first propose a blockchain enabled framework for the authentication of flight plans and exchanging authentication secrecy between UAS and ATM infrastructures in the preflight stage where reliable Internet connection is available to the UAS. We then provide a fountain code enhanced ADS-B protocol for the en-route authentication of UAS, and this protocol is seamlessly compatible with the de facto ADS-B ecosystem for ATC and ATM. More importantly, we theoretically prove the compatibility of this protocol in the de facto ADS-B systems.

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