7-2019

Decentralizing air traffic flow management with blockchain based reinforcement learning

Nguyen Binh Duong TA
Singapore Management University, donta@smu.edu.sg

Umang CHAUDHARY

Hong-Linh TRUONG

Decentralizing Air Traffic Flow Management with Blockchain-based Reinforcement Learning

Ta Duong, Ketan Kumar Todi[1], Umang Chaudhary
School of Computer Science and Engineering
Nanyang Technological University, Singapore

Hong-Linh Truong
Department of Computer Science, School of Science
Aalto University, Finland
linh.truong@aalto.fi

***Abstract*—We propose and implement a decentralized, intelligent air traffic flow management (ATFM) solution to improve the efficiency of air transportation in the ASEAN region as a whole. Our system, named BlockAgent, leverages the inherent synergy between multi-agent reinforcement learning (RL) for air traffic flow optimization; and the rising blockchain technology for a secure, transparent and decentralized coordination platform. As a result, BlockAgent does not require a centralized authority for effective ATFM operations. We have implemented several novel distributed coordination approaches for RL in BlockAgent. Empirical experiments with real air traffic data concerning regional airports have demonstrated the feasibility and effectiveness of our approach. To the best of our knowledge, this is the first work that considers blockchain-based, distributed RL for ATFM.**

***Index Terms*—decentralized optimization, air traffic flow management, blockchain, reinforcement learning, multi-agent systems**

I. Introduction

Air traffic flow management (ATFM) plays an important role in Air Traffic Control (ATC) systems, due to its significant impact on the efficiency and safety of air transportation. Increasing traffic volumes, constrained infrastructures and unpredictable weather conditions have been causing billions of dollars of lost yearly [1] when flights were delayed, cancelled or rescheduled. For improving local ATFM implementations, recent R&D interests emphasize the importance of collaborative decision making towards realizing global ATFM systems, e.g. the EU Single European Sky ATM Research (SESAR).

Due to continuing GDP growth over the last several decades, ASEAN is widely believed to be one of the fastest growing aviation market in the world. Air traffic volume in the region has been forecasted to triple by 2033 [2], putting more pressure than ever on the air transportation infrastructure. As a result, the ASEAN airspace is in need of a scalable ATFM solution which would be able to optimize traffic flows taking into account many domestic and international air transportation hubs in the region. This problem is difficult due to several fundamental challenges:

- ASEAN does not have a single political governing body, e.g. like the EU. It is not easy to convince other countries in the region to delegate the management of air traffic flows to a single ATFM system which is controlled and maintained by a centralized entity.
- High-fidelity, reliable mathematical models for accurate decision making is difficult to be implemented and maintained due to the complex and large airspace, conflicting priorities, unpredictable weather conditions, diverse needs and heavy traffic volumes in the region.
- Recent advances in monitoring, sensing and data acquisition techniques result in huge volumes of information related to air transportation from geographically distributed data sources, which are difficult to aggregate and to make sense of without the right analytics approach.

In this research, we aim to tackle the first major challenge, which is the lack of a centralized authority, in developing a scalable ATFM solution for the region. To this end, we propose and develop a decentralized ATFM solution based on the emerging blockchain technology, e.g., Hyperledger Fabric [3]. Our system is unique as it is the first to leverage the synergy between multi-agent systems with reinforcement learning (RL) [4] for air traffic flow optimization; and permissioned blockchain technologies such as Hyperledger Fabric for a secure, transparent and decentralized coordination platform. Specifically in this work, we design and develop BlockAgent, a scalable regional ATFM system, with the following contributions:

- Designing a novel coordination platform for distributed, multi-agent systems based on the emerging blockchain technology, in particular the Hyperledger Fabric ecosystem and its smart-contract/chaincode paradigm. Our platform provides the much-needed decentralized control capabilities required in a regional ATFM system.
- Implementing several distributed RL approaches in a decentralized multi-agent system for effective and adaptive ATFM operations over the blockchain-based infrastructure.
- Conducting extensive simulations and experiments of our system using actual regional air traffic data. The experiments have demonstrated the feasibility and effectiveness of our proposed approach.

The remainder of this paper is structured as follows. Section II summarizes important related work in the ATFM area; as well as well as the recent development of blockchain technologies. Section III discusses the BlockAgent approach, RL algorithms and implementation details. Section IV analyzes the experimental results obtained, and Section V concludes

[1]Currently at Manipal Institute of Technology, Manipal, India.

the paper with possible directions for future work.

II. Background and Related Work

A. Air Traffic Flow Management approaches

Most existing, published approaches in ATFM derive solutions in a local context, e.g., for a single Flight Information Region (FIR), using a centralized authority. They could be broadly classified into the following categories:

1) Eulerian/Lagrangian approaches: Lagrangian models [5] are used for modelling each aircrafts flight trajectories, which could be computationally intractable given large networks. Alternatively, Eulerian and other aggregate traffic models such as [6] and [7] describe a group of aircrafts via the concept of flows. The traffic flow management problem is usually formulated as an NP-hard integer programming problem [8] with various constraints such as aircraft types, speed limits, en-route sector capacity, etc. The aim usually is to minimize total departure and arrival schedule deviations.

2) Multi-agent systems: An adaptive, multi-agent approach seems like a good fit for the ATFM problem where there are complex interactions between unpredictable weather conditions, aircrafts, airports, traffic controllers, etc. Autonomous agents which are reinforcement learners have been designed to reduce air traffic congestion [4], [9], and [10]. In most existing approaches, an agent is associated with a fix (a 2D location), and could perform various actions for airplanes going through that fix, e.g., setting separations, imposing ground delays or carrying out reroutes. We note that the selection of agent reward functions may greatly impact the system performance.

Compared to the state-of-the-art approaches in ATFM, we argue that BlockAgent uniquely facilitates secure, decentralized and intelligent collaborative decision making for scalable ATFM operations in an environment where participants do not completely trust each other, or are not willing to give up their own decision making ability due to various economic or political factors. We believe that we are the first to introduce the emerging technology of blockchain to transform ATFM operations via decentralized optimizations.

B. Blockchain and applications

Bitcoin [11] has popularized the blockchain concept, which can be viewed as an immutable ledger for recording transactions. A blockchain is maintained by a network of untrusting participants using a consensus protocol. In a permissionless blockchain, such as Bitcoin, anyone can join anonymously. On the other hand, permissioned blockchains, e.g., those powered by Hyperledger Fabric, etc., only allow identified participants. In this way, permissioned blockchains enable secure interactions between entities having a common goal but do not fully trust each other. Such permissioned systems can operate without a cryptocurrency attached to the network [3]. Our proposed system, BlockAgent, takes advantages of permissioned blockchains to facilitate secure and transparent interactions between different stakeholders in a regional ATFM scenario with no centralized control. In BlockAgent, smart contracts (or chaincode in Hyperledger terms), which are actually arbitrary code installed and verified by all system participants, are responsible for the decentralized coordination of participants.

Blockchain has been used in a wide variety of financial applications [12]. New application domains including education, transportation, energy trading, etc. have been emerging recently. For instance, in [13], the authors proposed a globally trusted, decentralized credit and grading system for students and higher education institutions. In [14], blockchain has been proposed to establish secured, trusted and decentralized autonomous intelligent transportation systems (ITS). The main goal of ITS is to introduce information technology into the transportation infrastructure for improving road safety and traffic flows. Similarly, in [15], the authors considered a new communication network based on the decentralized property of blockchain to enable secure, distributed key management in vehicular communication systems.

More recently, novel and interesting applications of blockchain have been on the rise. In [16], an architecture for peer-to-peer energy markets has been proposed and evaluated. The main issue in such markets would be how to handle operational constraints and payments between microgrid participants without a central authority or aggregator. By leveraging blockchain, the authors demonstrated that trust, security and transparency between non-trusting participants could be ensured with smart contracts.

Early 2019, NASA researchers published a report describing a new prototype system [17] for mitigating security issues that may arise when adopting the new Automatic Dependent Surveillance System (ADS-B) mandated by the FAA. As present, air traffic service providers are able to preserve privacy regarding the flight plans, state, position, etc. for certain operations if required. However, the current FAA mandate for ADS-B does not include provisions for maintaining such aircraft-privacy options, and other potential malicious interferences such as spoofing or denial of service attacks. As a solution, the authors [17] proposed the application of Hyperledger Fabric [3] to enable air traffic privacy and anonymity. Our approach in this paper, BlockAgent, also employs a permissioned blockchain system based on Hyperledger Fabric, but our focus is on optimizing air traffic flows via decentralized multi-agent learning in an environment with no single ATFM authority.

III. The BlockAgent approach

A. Overview

Our proposed BlockAgent system is illustrated in Figure 1. It is decomposed into three layers:

1) Local Optimization: Each FIR could be responsible for local optimization of its own traffic flows based on locally available information. Traditional approaches involve Eulerian-Lagrangian flow models and operation research based methods [8]. Multi-agent systems with reinforcement learners have also been considered [4]. Local optimization ensures data privacy and security, and at the same time it retains the control over an entity's airspace. Each local solution could be

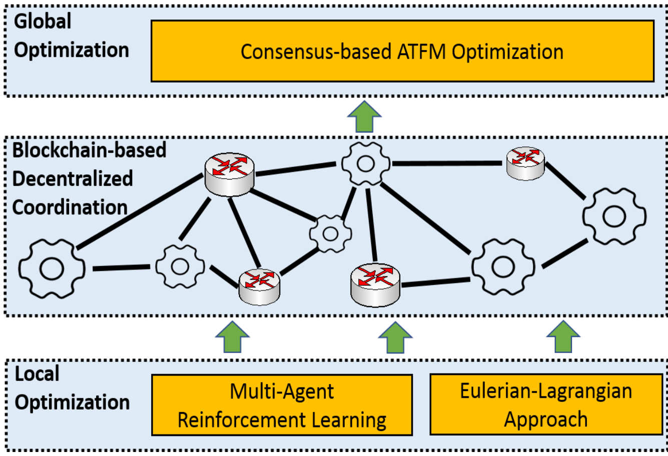

Fig. 1: The overall architecture of BlockAgent. The local layer is where stakeholders in the regional system can perform their own optimizations. The blockchain-based layer is responsible for providing distributed coordination mechanisms. In the global layer, smart contract/chaincode can be executed to aggregate locally obtained information. It is also for storing consensus-based global optimization results.

aggregated with others in the regional ATFM system to form globally optimal solutions.

In this work, we design a decentralized multi-agent federation to manage the traffic flows for many different airports spanning regional (ASEAN) countries. In this federation, an FIR or an airport maintains its own agents to handle local optimization operations. We then implement several RL approaches for the agents to perform local optimizations. More details on the RL algorithms are given in subsequent sections.

Agents in our system will need to exchange information and to coordinate their actions to benefit the federation as a whole. Such communication and coordination between autonomous agents located in different FIRs will be facilitated using the blockchain-based platform detailed below.

2) Blockchain-based Decentralized Coordination: We choose to work with the Hyperledger Fabric framework, and deploy a permissioned blockchain system with proper authentication and identification of participants. Our system forms a private chain to store information relevant to the global optimization layer. Over this structure, appropriate chaincode/smart contract will act as a decentralized coordinator to derive a global, consensus-based solution taking into account various local information given by the system participants.

One particular design issue is the performance of blockchain-based systems. Permissioned systems like Hyperledger Fabric offers much higher throughput compared to permissionless blockchains such as Ethereum [18]. Nevertheless, our system design aims to reduce the amount of blockchain-based data and transactions for better performance. For instance, a blockchain peer which represents a particular airport of FIR would only write local data relevant to the optimization into the ledger, e.g., the total local delay at the particular airport. Such design would reduce the amount of on-chain data and the number of transactions, which in turns leads to better runtime performance.

3) Global Optimization: At this layer, smart contracts/chaincode which can contain arbitrarily complex logic will act as distributed coordinators for aggregating local optimization results. The globally optimized solutions could be stored persistently on-chain for future usage and auditing purposes. The immutable ledger ensures that the global optimization decisions are secure and tamper-proof. We also note that the coordination chaincode is installed at every system participant, i.e., peer node in Hyperledger terms. In this way, the global optimization logic is transparent and verifiable by all stakeholders in the system.

In the prototype version of BlockAgent, we implement several novel coordination mechanisms. In particular, a RL agent can invoke a specific chaincode to obtain globally optimized rewards for its local actions. Although simple, such a mechanism enables very effective coordination between distributed and potentially untrusting participants so that they can reach a common goal.

B. Novelty

We argue that the synergy between the emerging permissioned blockchain technology [3] and multi-agent systems offer a natural solution to transform regional ATFM operations in an intelligent, decentralized, transparent and secure manner:

1) Decentralization: For big and complex scheduling/optimization problems, decentralized approaches are widely used: smaller sub-problems are obtained and solved independently in parallel, and then a final solution could be derived using some aggregation algorithms. Although scalable, such an approach requires trust and complete data sharing between the participants which might not be always possible. BlockAgent leverages the blockchain's decentralized control feature to facilitate distributed, cooperative decision making in trustless environments.

2) Security and Transparency: Decentralized optimization approaches normally lack protection against cyberattacks [16]. Furthermore, they are more likely to reveal private or confidential information about each system participant. This is especially a concern for an ASEAN-wide ATFM system in which no central authority could possibly enforce system-wide policies and regulations. This scenario represents a promising use case for leveraging tamper-proof, visible and verifiable smart contracts on the blockchain to provide a consensus-based approach to the regional ATFM problem.

3) Intelligence: BlockAgent provides the decentralized communication infrastructure for the combination of existing ATFM optimization approaches, e.g., Eulerian/Lagrangian or multi-agent systems, etc. A plausible scenario is that many airports or countries participating in this system would like to retain whatever ATFM approaches they have been developing and using. BlockAgent therefore enables the possibility of aggregating optimization solutions produced individually over a consensus-based mechanism. We hypothesize that such an approach could enable more intelligent and practical collaborative decision making, which are highly desirable features in next-generation ATFM systems.

C. Reinforcement Learning for Regional ATFM

Note that in this paper, due to safety guidelines and political factors, we do not address the flow management problem [9] at the aircraft separation or the dynamic airspace configuration level. We instead focus on managing regional flows with a time horizon of 1-8 hours [4]. Each agent in the distributed federation aims to select an action that would lead to the best overall system performance.

In this paper, the main goal is to reduce the overall delay for all flights operating in the region managed by BlockAgent. The total delay experienced in an ATFM system can be divided into two components: i) in-air delay (denoted as I), in which arriving planes have to wait in-air due to congestion; and ii) ground delay (denoted as G) in which departing planes wait on the ground before taking off. The multi-agent system aims to minimize the total system penalty P which is expressed by:

$$P = G \times \alpha + I \times \beta \tag{1}$$

where α and β are the pre-determined weights for in-air and ground delay, respectively. Usually, it is better for planes to wait on the ground in case of congestion [4].

The agents use a reward function which is maximized via a RL algorithm. In this paper, we make use of immediate rewards, i.e., the agent can take an action a and a reward R would be given. The particular actions that agents can take in an ATFM scenario could be setting ground delays for flights, adjusting the miles-in-trail parameter, or rerouting the planes. In the BlockAgent prototype, we consider setting appropriate ground delays to ease congestion and improve end-to-end delay for all flights. The reward function should be designed so that agents can learn to gradually minimize the system penalty P over time. The ϵ-greedy RL algorithm [19] is then used to update the new value $V(a)$ of an action a as follows:

$$V(a) \longleftarrow \lambda \times R + (1 - \lambda) \times V(a)_c \tag{2}$$

where λ is the learning rate of the RL algorithm, and $V(a)_c$ is the current value of action a. In each learning episode, the agent will choose: i) the best action a in terms of value $V(a)$ with probability $1 - \epsilon$; or ii) a randomly selected action with probability ϵ. In this way, the ϵ value is used to balance the trade-off between exploitation and exploration for the reinforcement learners [19].

The ϵ-greedy RL algorithm has been known to work well in centralized ATFM systems [4], in which each agent can take local actions and obtain corresponding rewards using a predefined reward function. However, this method is not applicable to a decentralized ATFM system in which no single entity can decide on the reward function for the system. To address this problem, we leverage the Hyperledger's chaincode paradigm to implement a consensus-based approach to RL reward function and distributed agent coordination. In particular, we consider three different methods for agents to take action and to obtain a corresponding reward. We note that these methods are not the only possibilities: new coordination approaches could be developed and plugged into the BlockAgent architecture in a straightforward manner.

1) Global reward - local action: In this method, each agent in the system will take independent actions and record their local system's performance onto the distributed ledger. The agents then receive a coordinated, consensus-based reward. Such reward function is implement as a chaincode on the Hyperldeger blockchain in which each agent is a member. In this way, the code for the reward function is transparent and verifiable by all members of the system. It is also tamper-proof: any unauthorized modifications would not be committed into the blockchain. In our implementation, the global reward is computed by aggregating all local delays recorded on the blockchain to produce the total system penalty P. This method is named the $global$ algorithm.

2) Global reward - synchronized action: This is similar to the above method: a chaincode would be used as a distributed control mechanism for agents to coordinate their actions by making use of the same reward function. On top of that, agents' actions can also be synchronized using another chaincode. For instance, this chaincode can compute appropriate ground delay values which are to be set by different distributed agents. As a results, both the actions and rewards in a decentralized RL system could be coordinated. This method is named the $synchronized$ algorithm.

3) Local reward - local action: This method serves as a baseline for performance comparison. The decentralized RL system functions without a coordinator, i.e., agent would take actions to minimize its own local reward. For example, an agent in charge of flow management for an airport can learn to set appropriate ground delays for the airport's planes with the aim of reducing the overall delay at this airport only. In this approach, there is no need for a blockchain-based coordination mechanism. This method is named the $local$ algorithm.

D. System Implementation

We have implemented a prototype of the BlockAgent system using Hyperledger Fabric as the blockchain-based coordination layer. The system has been deployed over a distributed system in our lab. Each node in the system run Ubuntu 18.04 with 16GB of memory. We install on the nodes the latest stable versions of Python, cURL, Docker, Docker Compose, Node.js, npm, Go and the Docker Images for Hyperledger Fabric. Each agent is implemented as a peer node in the permissioned blockchain. Agents' actions are coordinated when needed using appropriate chaincodes installed at each peer in the system.

We have also developed a simple air traffic flow simulator to evaluate the proposed RL approaches described above. Actual flight routes have been obtained from $flightradar24$ and imported into the simulator. Our implementation can simulate random events such as unexpected congestion at airports due to limited number of runways and high traffic volume, or randomized arrival times due to weather patterns, etc.

The implemented system can work in both standalone and blockchain-based mode. In the standalone mode, we have a centralized ATFM system which controls all agents. This mode has been used as a platform for experimenting with various RL algorithms first, as we need to make sure that they work before implementing them on the blockchain.

IV. Evaluation and Results

A. Methodology

1) Flight data: We construct a dataset using 5 ASEAN airports, namely, Singapore (SIN), Kuala Lumpur (KUL), Bangkok (BKK), Ho Chi Minh City (SGN) and Jakarta (CGK). Every flight between these airports has been taken into account, as obtained from $flightradar24.com$. All the flight dates and times are considered with regard to the respective airport's timezone. The dataset consists of 353 flights between the above five airports. Every flight has its scheduled date and time of departure, departure airport name and code, scheduled date and time of arrival, arrival airport name and code.

2) RL parameters: In each simulation episode, an agent would take an action, and then receive a corresponding reward for the value of that action using Equation (2). The ϵ value is set to 0.25, i.e., the agents would explore with a probability of 25%. The learning rate λ is set to 0.5. We have experimented with different values of ϵ and λ. However, the learning seemed to be faster and more stable with the above values.

In the experiments, the reward function is defined as $\frac{N}{P}$, in which N is set to a large, positive integer, e.g., 10000; and P is the system penalty defined in Equation (1). In this way, the agents aim to minimize the system penalty directly. To compute P, we set $\alpha = 1$ and $\beta = 5$, i.e., in-air delay has been given more importance compared to ground delay.

B. Results and Analysis

1) Performance of RL algorithms in standalone mode: Fig. 2 compares the three proposed RL algorithms. We observe that they all seem to be working well in reducing the system penalty, which is designed to reduce the overall flight delays in the system of 5 airports. The $synchronized$ algorithm, which controls both the ground delay values set by each agent and the global reward function, outperforms the other two. This is an indication that our RL approaches could work to effectively reduce the overall system delay.

We notice that the performance improvement of the $synchronized$ algorithm could get even better when we introduce randomness into flight arrival times. The results are shown in Fig. 3. In our experiments, a random amount of time (in minutes) in the range of [-30, 30] is added to around 25% of flights randomly selected from the dataset. The observation is that, all the three proposed approaches seem to be resilient to random arrival times. As demonstrated in the figure, the $global$ and $synchronized$ algorithms can reduce the system penalty much more, compared to the $local$ algorithm. This demonstrates that if an appropriate coordination mechanism can be implemented between distributed stakeholders, the regional system as a whole can benefit greatly.

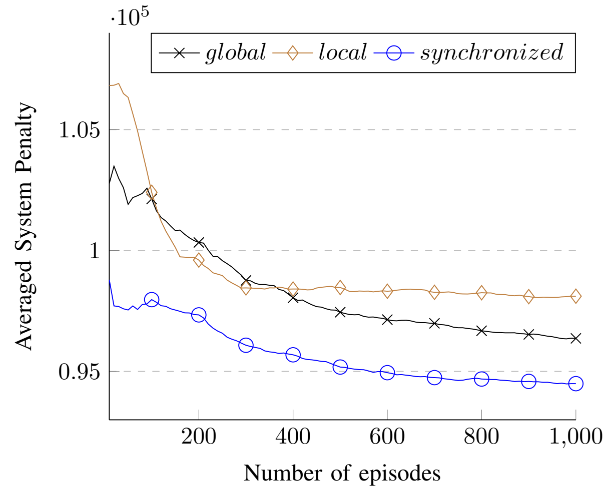

Fig. 2: Comparing three different RL algorithms in the standalone mode. We observe that they all seem to be working in reducing the system penalty. The $synchronized$, which coordinates both the ground delay values and system reward function, outperforms the other two.

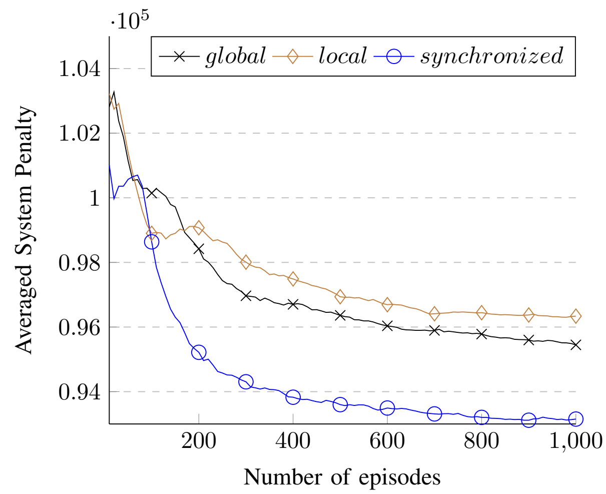

Fig. 3: We introduce random delays in the range of [-30, 30] minutes to 25% randomly selected flights in the dataset, standalone mode. The $synchronized$ appears to be even better than the other two algorithms.

2) Performance of RL algorithms in blockchain-based mode: Fig. 4 illustrates the results obtained when running all the three RL algorithms in the decentralized blockchain mode. The coordination between different airports in this system is carried out by Hyperledger Fabric chaincode which is automatically installed and verified by each system participant. A system participant, e.g., an airport, is represented by a peer node in the Hyperledger Fabric blockchain. Each peer node runs on a different networked server.

We note that the $global$ algorithm, in which each agent is free to make its own local actions but receive coordinated system reward computed by a chaincode, performs the best in this case. The *synchronized* algorithm is still quite effective in the decentralized implementation, but is outperformed by the *global* algorithm. This might be due to network and various processing delays in the distributed system and blockchain. For instance, communication and computation via our blockchain implementation incur more than 2x latency compared to the standalone mode. As a result, distributed peers might not be perfectly synchronized as in the standalone implementation. Nevertheless, the results in Fig. 4 demonstrate that an appropriate blockchain-based coordination mechanism, e.g., the *global* algorithm, could be effective in reducing overall system delay, especially when compared to the case without any coordination of agents.

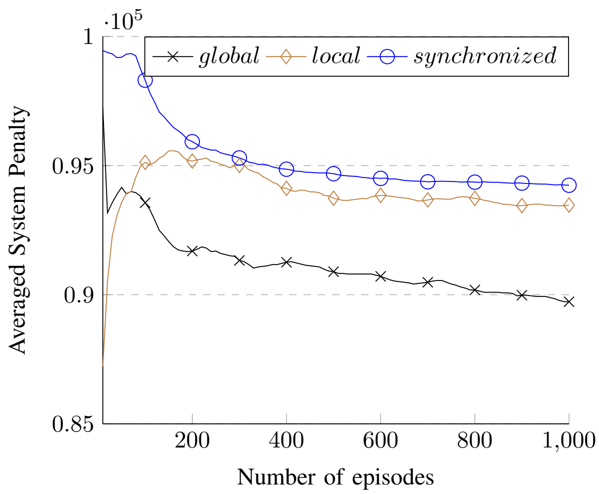

Fig. 4: Comparing three different RL algorithms in the blockchain-based implementation. The *global* algorithm, in which the agents are free to decide their own local actions but are coordinated using a system reward function, appears to be the best here.

V. Conclusion

In this paper, we have proposed BlockAgent, a decentralized approach designed to address regional ATFM issues. BlockAgent considers the scenario in which there is no centralized authority for enforcing system-wide policies due to various economic or political factors. BlockAgent leverages the synergy between: i) permissioned blockchain technologies such as Hyperledger Fabric for secure, transparent and decentralized optimization; and ii) multi-agent reinforcement learning systems for intelligent decision making, to offer a natural solution for the regional ATFM problem.

We have implemented and evaluated a prototype of BlockAgent running over a distributed computer system. The results obtained confirm the feasibility and effectiveness of our approach. We believe that this blockchain-based multi-agent approach renders a novel technical pathway for transforming ATFM systems spanning countries. We are currently working on new learning algorithms and blockchain optimization to enable much larger-scale experiments of BlockAgent.

Acknowledgement

This research has been supported via the Academic Research Fund (AcRF) Tier 1 Grant RG135/18.

References

[1] B. Zou and M. Hansen, "Flight delay impact on airfare and flight frequency: A comprehensive assessment," *Transportation research part E: logistics and transportation review*, vol. 69, pp. 54–74, 2014.

[2] Z. W. Zhong, "Overview of recent developments in modelling and simulations for analyses of airspace structures and traffic flows," *Advances in Mechanical Engineering*, vol. 10, no. 2, 2018.

[3] E. Androulaki, A. Barger, V. Bortnikov, C. Cachin, K. Christidis, A. De Caro, D. Enyeart, C. Ferris, G. Laventman, Y. Manevich, *et al.*, "Hyperledger fabric: a distributed operating system for permissioned blockchains," in *Proceedings of the Thirteenth EuroSys Conference*, p. 30, ACM, 2018.

[4] A. K. Agogino and K. Tumer, "A multiagent approach to managing air traffic flow," *Autonomous Agents and Multi-Agent Systems*, vol. 24, no. 1, pp. 1–25, 2012.

[5] D. Bertsimas and S. S. Patterson, "The air traffic flow management problem with enroute capacities," *Operations research*, vol. 46, no. 3, pp. 406–422, 1998.

[6] Y. Zhang, R. Su, G. G. N. Sandamali, Y. Zhang, and C. G. Cassandras, "A hierarchical approach for air traffic routing and scheduling," in *2017 IEEE 56th Annual Conference on Decision and Control (CDC)*, pp. 6277–6282, IEEE, 2017.

[7] A. M. Bayen, R. L. Raffard, and C. J. Tomlin, "Eulerian network model of air traffic flow in congested areas," in *Proceedings of the 2004 American Control Conference*, vol. 6, pp. 5520–5526, IEEE, 2004.

[8] Y. Zhang, R. Su, Q. Li, C. G. Cassandras, and L. Xie, "Distributed flight routing and scheduling for air traffic flow management," *IEEE Transactions on Intelligent Transportation Systems*, vol. 18, no. 10, pp. 2681–2692, 2017.

[9] M. Molina, S. Carrasco, and J. Martin, "Agent-based modeling and simulation for the design of the future european air traffic management system: The experience of cassiopeia," in *International Conference on Practical Applications of Agents and Multi-Agent Systems*, pp. 22–33, Springer, 2014.

[10] G. Gurtner, C. Bongiorno, M. Ducci, and S. Miccichè, "An empirically grounded agent based simulator for the air traffic management in the sesar scenario," *Journal of Air Transport Management*, vol. 59, pp. 26–43, 2017.

[11] S. Nakamoto *et al.*, "Bitcoin: A peer-to-peer electronic cash system," 2008.

[12] M. Pilkington, "Blockchain technology: principles and applications," *Research handbook on digital transformations*, vol. 225, 2016.

[13] M. Turkanović, M. Hölbl, K. Košič, M. Heričko, and A. Kamišalić, "Eductx: A blockchain-based higher education credit platform," *IEEE Access*, vol. 6, pp. 5112–5127, 2018.

[14] Y. Yuan and F.-Y. Wang, "Towards blockchain-based intelligent transportation systems," in *2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)*, pp. 2663–2668, IEEE, 2016.

[15] A. Lei, H. Cruickshank, Y. Cao, P. Asuquo, C. P. A. Ogah, and Z. Sun, "Blockchain-based dynamic key management for heterogeneous intelligent transportation systems," *IEEE Internet of Things Journal*, vol. 4, no. 6, pp. 1832–1843, 2017.

[16] E. Münsing, J. Mather, and S. Moura, "Blockchains for decentralized optimization of energy resources in microgrid networks," in *2017 IEEE Conference on Control Technology and Applications (CCTA)*, pp. 2164–2171, IEEE, 2017.

[17] R. J. Reisman, "Air traffic management blockchain infrastructure for security, authentication, and privacy," 2019.

[18] C. Dannen, *Introducing Ethereum and Solidity*. Springer, 2017.

[19] R. S. Sutton and A. G. Barto, *Reinforcement learning: An introduction*. MIT Press, 2018.