Market Structures for Service Providers in Advanced Air Mobility

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Proposed concepts of operations for advanced air mobility rely on private service providers being responsible for providing air traffic management services to uncrewed aircraft such as drones and autonomous air taxis. While such proposals are unprecedented in the aviation context, one can draw parallels to the Internet and the role played by Internet service providers in managing web traffic. A study of the evolution of the Internet illustrates that, without clear rules for cooperation around a nascent market, private profit motives incentivize against service provider cooperation, especially for traffic flows that traverse multiple regions managed by different service providers. To address this problem, we propose a profit-sharing mechanism based on the Shapley value that incentivizes service providers to cooperate. We show that this mechanism i) ensures that service providers route flights along globally optimal routes, and ii) encourages service providers to work together in providing more efficient routes. We study the allocation of sectors to service providers and show that different allocations can cause large differences in profit earned. Finally, we discuss some of the remaining challenges with having a federated network of private service providers supporting traffic management for advanced air mobility operations.

I. Introduction

THE EXPECTED proliferation of advanced air mobility (AAM) in the near future requires the coordination of orders of magnitude more flights than are currently supported [1]. Current estimates of the density, type, and number of these new flights [2] have led the Federal Aviation Administration (FAA) in the United States to declare that "existing Air Traffic Management (ATM) System infrastructure and associated resources cannot cost-effectively scale to deliver services" [3]. While current systems focus primarily on fixed-wing aircraft, scheduled flight operations, and airport infrastructure, AAM includes novel vertical takeoff and landing (VTOL) aircraft and uncrewed aircraft systems (UAS) flying on-demand, with origin and destination locations potentially far away from existing airports. These characteristics necessitate novel air traffic management tools and strategies, built to support AAM aircraft and use cases, that work in conjunction with existing air navigation service providers (ANSPs) to safely and efficiently realize new aerial transport opportunities [3–5].

The FAA in the United States has proposed two concepts of operations for AAM: UAS traffic management (UTM) for low-altitude operations of small UAS [3], and urban air mobility (UAM) for operations of larger cargo- and passenger-carrying aircraft in "UAM corridors" [4]. In these respective contexts, UAS service suppliers (USSs) and providers of services for UAM (PSUs) enable these novel operations, working alongside but independent of current air traffic control services. Other regions, including Europe and Japan, have similar frameworks for AAM [5,6].

USSs and PSUs play central roles in the proposed system architectures for UTM and UAM [3,4]. Furthermore, these roles are expected to be carried out by third-party service providers (SPs) with FAA oversight [4]. Throughout the remainder of this paper, unless explicitly stated otherwise, we use "service provider" (SP) to refer to any AAM SP, encompassing both USSs and PSUs. In general, SPs are expected to support a wide range of aircraft operator needs, ranging from operational planning to communication to traffic management. This work focuses on the last of these services: Similar to how the FAA currently provides traffic management services to crewed aircraft, we consider *how SPs will provide traffic management support for autonomous aircraft*.

While there has been considerable focus on the certification and operation of novel aircraft for AAM, the roles of an SP are only loosely defined today. The following list summarizes some of the envisioned characteristics and responsibilities of SPs:

1) SPs will perform strategic deconfliction (preflight planning to account for anticipated traffic demand and capacity, in-flight rerouting for disruptions, etc.) of AAM flights. In contrast, AAM operators, aided by SPs, will perform tactical deconfliction (in-flight collision avoidance) of flights [4].

2) SPs will support AAM operations through the exchange, analysis, and mediation of information among AAM flight operators, SPs, the FAA, and other stakeholders. The proposed architecture is a federated network of SPs [4]. Such federated architectures—comprising of connected, semi-autonomous components—were first proposed in the context of databases [7,8], and have since been applied to the Internet [9].

3) SPs will form a network to enable every AAM flight to traverse through the airspace sectors it needs to access, even if its directly-partnered SP does not manage airspace in that sector.

4 SPs will primarily be *private sector entities*, although public sector SPs may also exist [10].

5) SPs may overlap in their geographical service regions [3].

6) SPs may also be AAM flight operators, as long as they satisfy the relevant qualifications.

These envisioned characteristics are still loosely defined and may be in conflict with each other. In particular, if SPs are private entities (as envisioned for the AAM context), *competition for customers and profit among SPs may be in opposition to the cooperation necessary for safely moving flights between airspace regions managed by different SPs.* Even if regulatory frameworks require that SPs cooperate in the movement of AAM flights, SPs may be incentivized to route certain flights in inefficient or unfair ways. Such inefficient emergent behavior has been observed in other traffic management contexts, such as in the growth of the Internet [11,12].

To address these concerns, and to incentivize collaboration among traffic management SPs, we propose a profit-sharing mechanism using the Shapley value [13]. This method divides the total revenue earned from supporting a flight in a fair manner among SPs based on their costs and contributions to the flight. We show that, under this mechanism, an SP maximizes its own profit if it routes flights along the globally shortest path, even if the SP incurs a higher individual cost. Furthermore, the SP is incentivized to support other SPs in the presence of disruptions. This paper focuses on the first five of the

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desired characteristics listed above, leaving the last (SPs also operating flights) as a topic for discussion and future research.

The rest of this paper is organized as follows: We first give a brief history of Internet traffic routing, and draw comparisons to AAM traffic management in Sec. II. Models of airspace and of profit-sharing mechanisms are presented in Sec. III. In Sec. IV, we describe the Shapley value, a method of fair division of rewards among a coalition of agents that satisfies several desirable properties. Experimental results comparing the Shapley value against other profit- and revenue-sharing mechanisms are shown in Sec. V. The importance of sector allocations to different SPs is discussed and studied in Sec. VI. Section VII addresses possible challenges with using the Shapley value, a possible concept of operations for flight operators and SPs under the Shapley value, and interesting directions for further investigation. Finally, Sec. VIII concludes this work.

II. Background

The provision of Internet traffic serves as a recent example of a federated, decentralized routing system run mostly by private companies. In this section, we give a brief summary of the history of Internet economics, draw parallels between the Internet and AAM traffic management, and note some key differences that prevent the direct application of market structures used in the Internet to the AAM context. We also provide related work.

A. Internet as a Model for Advanced Air Mobility

One example of a networked infrastructure that evolved from centralized to decentralized management and from a public to private SPs is the Internet. Over the past 25 years, the Internet has grown into one of the most innovative parts of society and a mainstay of modern life. Like the proposed AAM architectures [3], the Internet is a collection of federated and decentralized services, with private Internet service providers (ISPs) managing different local and regional routes for data packets to traverse [14]. ISPs are independent entities that transport information to and from many different Internet users and other ISPs. AAM SPs serve a similar role in the aviation context, so tracing the development of the Internet can inform how traffic management for AAM may evolve and help illustrate possible problems.

1. Parallels to the Internet

The proposed vision for AAM mirrors the development of the Internet, where the responsibility of routing and managing traffic begins with public entities before transitioning to private entities. The Internet in the U.S. began with government-funded efforts culminating in NSFNET, a transcontinental Internet backbone supported and operated by the National Science Foundation (NSF) to connect its supercomputers to various research and academic networks. Participation in NSFNET came at no cost to institutions, but the variety of use cases and traffic volume on the Internet eventually ballooned to a degree that the government could not sustainably support [15].

In the mid-1990s, companies began developing private fiber-optic networks to carry the growing volume of commercial Internet traffic, forming the first ISPs. These new ISPs, driven by profit motives and high demand, expanded rapidly and eventually became the Internet that we know today [16].

There are clear parallels between the growth of the Internet and the forthcoming wave of AAM. Today, air traffic controllers, largely employed by public ANSPs (e.g., the FAA), are responsible for all traffic flow management, much like how the government-supported NSFNET initially formed the backbone of the Internet. As the volume and variety of AAM operations increase, conventional ANSPs will not be able to manage all airborne operations. It is envisioned that private entities will form a distributed network of federated SPs to perform routing and other services [3]. Competition between these SPs will result in a better quality of service for the AAM aircraft operators that contract with them. The expectation is that private SPs will adapt better than their public counterparts to the pace of technological innovation, the increase in flight volumes, and the dynamic, on-demand requirements of AAM operations.

B. Differences Between the Internet and AAM

While the Internet has been remarkably successful in connecting the world, key differences between the Internet and aviation contexts prevent us from directly adapting ISP operating paradigms to AAM.

Internet traffic is routed via ISPs and follows a settlement-free peering model. This is a "sender-keeps-all" system in which each ISP only profits from its own customers [11]. The effectiveness of this model hinges on one of two conditions: i) traffic in both directions must be approximately equal, or ii) secret bilateral deals between ISPs must compensate for imbalanced traffic flows. However, both of these conditions are far from guaranteed in the AAM context. While certain types of traffic demand (e.g., commutes) may be approximately symmetrical, traffic from other applications, such as drone package delivery, is far more likely to be directional (e.g., from a warehouse to customers). If the SP covering the vertiport near the warehouse kept all revenue from the drone operator, there would be no incentive for other SPs to cooperatively route flights through the airspaces that they serve. Furthermore, secret bilateral deals between SPs pose a safety concern, as the lack of transparency could create a culture of competition and distrust in inter-SP relations and obfuscate critical SP operations from regulatory agencies. Even for ISPs, these deals have been an occasional source of dramatic disagreements. For example, a dispute between Level 3 and Cogent severed 15% of the Internet for three days in 2005 [11,17]. Such breakdowns would be extremely undesirable for emerging AAM applications.

Even with steady revenue streams, there are operational concerns with directly using the ISP model for AAM SPs. In the Internet, TCP/IP deals with congestion through the graceful handling of dropped packets. If part of the network is congested, packets are dropped and then retransmitted to improve reliability. In the airspace context, dropping a flight—literally—is a major safety issue and unacceptable in any proposed approach. Instead, SPs will need to manage congestion by cooperating to reroute or delay flights entering and exiting their regions of responsibility.

Finally, the sender-keeps-all revenue structure of the Internet incentivizes "hot-potato" routing, in which an ISP passes data along the path of least cost to itself, even if that path may degrade service quality for the customer [18]. Such routing leads to inefficiencies such as increased delays, longer routes traveled, and greater energy consumption. While this may be acceptable in the Internet context, inefficient aircraft routing wastes fuel, causes flight delays, and decreases system safety.

The gradual evolution of the Internet has built up industry inertia and resistance to any change in established market structures. By contrast, the absence of a status quo presents an unprecedented opportunity to design a *clean-slate* market structure that encourages cooperation between traffic management SPs while being compatible with the AAM concept of operations.

C. Related Work

Market-based approaches have been studied for strategic demand management and tactical deconfliction in the aviation context, including airport slot auctions [19] and slot trading during Ground Delay Programs [20]. More recent work has discussed using market mechanisms for airspace resources. Brugnara et al. [21] present a centralized market for trading airspace time windows. Decentralized protocols for cost-aware airspace allocations are presented in [22,23]. While all of these works use pricing and markets for aviation resources, they are centered on the interaction of air traffic management SPs with aircraft operators, and not the interaction between SPs.

Network managers (which are analogous to SPs) [24] exist in the European airspace network, which play a role in traffic management by assigning delays to flights to ensure capacity restrictions are followed. A more market-driven role for the network manager is proposed in [25], where the manager serves as the middleman between Air Navigation Service Providers (ANSPs) and aircraft operators by pricing trajectories and routes. The network manager creates a method for

ANSPs to coordinate specific routes with operators, but it does not directly facilitate coordination between ANSPs.

The early history of Internet pricing and economics is well-covered in [15], which describes some of the basic properties of “sender-keeps-all” economics. A deeper explanation of interconnection and Internet structures is given in [18]. Ma et al. outline the concerns with “hot-potato routing” in [12,26], with an accompanying solution of profit-sharing based on the Shapley value [13]. We adapt these concepts to the context of AAM.

Shapley profit-sharing mechanisms have also been proposed alongside other mechanisms in the context of road logistics and multimodal transportation networks. Three profit allocation methods are studied in [27] for carrier collaboration in pickup and delivery services, including one based on the Shapley value. They focus on the sharing of packaged delivery of vehicles transiting an open road network, while our work centers on the sharing of exclusive airspace access. A Nash bargaining solution is used in [28] to establish cooperation between services in multimodal passenger transport. The theoretical analysis provided focuses on passenger flow behavior in response to pricing.

III. Modeling

We now present a sectorized model of a two-dimensional airspace and a flight’s route through that airspace, as well as a mechanism for profit-sharing among SPs. These will be used in the remainder of this work.

A. Airspace Structure and Flight Routing

We structure the airspace as a set of n sectors indexed by sector IDs $\mathcal{S} = \{1, 2, \ldots, n\}$, where each sector ID $j \in \mathcal{S}$ corresponds to a closed, bounded polygon sector $S_j \subseteq \mathbb{R}^2$. A point not in any sector of $\mathcal{S}$ is considered to be out of the airspace. Without loss of generality, we assume that every pair of adjacent sectors has “gates” spaced evenly along their border; we will prove later that SPs are always incentivized to create gates. These gates simplify the calculations that reveal the impact of profit-sharing on routing decisions. Gates are the only points of overlap between sectors, i.e., for adjacent sectors $S_i, S_j \in \mathcal{S}$ with gates $g_{(ij,1)}, g_{(ij,2)}, \ldots$, the overlap is $S_i \cap S_j = \{g_{(ij,1)}, g_{(ij,2)}, \ldots\}$.

We denote the set of SPs as $\mathcal{P} = \{P_1, \ldots P_p\}$, where $P_k \in \mathbb{Z}$ corresponds to an independent SP. Sectors are assigned to SPs through an allocation function $\mathcal{A}: \mathcal{S} \to \mathcal{P}$. We assume for now that each sector has a unique and independent SP that is responsible for only that sector. As such, the allocation of sectors is simply $\mathcal{A}(j) = P_j$. We will use SP and sector interchangeably for now; in Sec. VI, we will introduce new notation to distinguish between the two. Figure 1 shows this structure applied to a small region of airspace.

Next, we look at the flights traveling through the airspace. Consider a flight $f \in \mathcal{F}$ traveling between an origin $o \in S_q$ and destination $d \in S_{q'}$, with $q, q' \in \mathcal{S}$. This flight can take a route $r^f(o, d) = [r_1, r_2, \ldots, r_m]$ made up of a sequence of vectors, or route segments, with $r_i^f \in \mathbb{R}^2$. These vectors define a sequence of waypoints

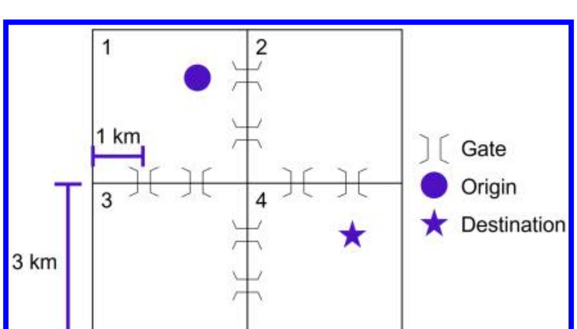

Fig. 1 Model of airspace consisting of four (numbered) sectors. Gates between adjacent sectors are the only locations where flights may cross a border. Each sector is served by one unique SP, where $\mathcal{A}(j) = P_j$.

$W^f = [w_0^f, w_1^f, \ldots, w_m^f]$, $w_i^f \in \mathbb{R}^2$, where $w_0^f = o$, $w_m^f = d$, and $w_i^f = w_{i-1}^f + r_i^f \; \forall \, i \in \{1, \ldots, m\}$. For brevity, because we typically discuss a single flight at a time, we write $r^f(o, d)$ as r^f. We will write a generic route not associated with any flight as r.

A subset, or coalition, of sectors is denoted by $S \subseteq \mathcal{S}$. When such a coalition is formed, only routes that are fully contained in $\bigcup_{j \in S} S_j$ (i.e., that fully lie within the union of the sectors in S) are available. We define the set of valid routes as follows: For a coalition $S \in \mathcal{S}$, the set of valid routes $R^f(S)$ for a flight f between o and d is the set of route segments, where the first segment starts at o, the last segment ends at d, and the start of a segment is the termination point of the previous segment:

$$R^f(S) = \{r^f | w_0^f = o, w_m^f = d, w_i^f = w_{i-1}^f + r_i^f, w_{i-1}^f + \theta r_i^f \in S_j, \forall r_i^f \in r^f, j \in \mathcal{S}, \theta \in [0, 1]\} \tag{1}$$

This definition adds the requirement that all points along a route must be within a sector that is in the coalition. The SP P_j responsible for S_j has control of r_i^f, and it may be responsible for more than one route segment at a time.

B. Profit and Profit-Sharing

We now define the value functions used for our analysis. The revenue of a coalition $u^f(S)$ for a given flight is

$$u^f(S) = \begin{cases} U^f, & \text{if } |R^f(S)| \geq 1 \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

where $U^f: (o, d) \to \mathbb{R}$. The condition $|R^f(S)| \geq 1$ implies that revenue is nonzero only if there is at least one route between the origin and destination for a given coalition S. In this work, we let $U^f = 2\|o - d\|_2$, or twice the Euclidean distance between o and d.

The cost of a route segment is given by a function $c(r_i): r \to \mathbb{R}_{\geq 0}$, that increases monotonically with the length of the segment $\|r_i\|_2$. We extend this definition to a route, with $c(r) = \sum_{r_i \in r} c(r_i)$. This cost only exists if a valid path exists in S:

$$c^f(S, r^f) = \begin{cases} c(r^f) & \text{if } r^f \in R^f(S) \\ 0 & \text{o.w.} \end{cases} \tag{3}$$

For this work, we define $c(r_i) = \|r_i\|_2$, the Euclidean length of a route segment. The cost of a route for a sector for flight f is the sum of costs for all route segments in the sector: $c_j^f(r^f) = \sum_{r_i^f \in r^f, r_i^f \in S_j} c(r_i^f)$.

Then the value, or profit, of a route r^f for a given flight f and a given coalition S is $v^f(S, r^f) = u^f(S) - c^f(S, r^f)$. We define $v^f(S, R^f)$ as the maximum profit over the set of routes $R^f(S)$:

$$v^f(S, R^f) = \max_{r^f \in R^f(S)} v^f(S, r^f) \tag{4}$$

We can also determine the marginal value of adding sector $j \notin S$ to coalition S for flight f as $\Delta_j^f(v^f, S) = v^f(S \cup \{j\}) - v^f(S)$, and $\Delta_j^f(v^f, S, R^f) = v^f(S \cup \{j\}, R^f) - v^f(S, R^f)$ if limited to a particular set of routes R^f.

We now describe the mechanism for dividing the earnings from a flight. Let a profit-sharing mechanism ϕ be defined as $\phi(\mathcal{S}, v^f) = \phi^f = \{\phi_1^f, \ldots, \phi_n^f\}$, where for some value function v^f, $\phi_j(\mathcal{S}, v^f) = \phi_j^f$ returns a value in $\mathbb{R}_{\geq 0}$ for each sector $j \in \mathcal{S}$. This is the profit a sector (in reality, an SP) earns from the mechanism. We write $\phi_j(S, v^f)$ to represent the profit earned from a subsystem where all SPs not in the coalition (i.e., in the subset $\mathcal{S} \setminus S$) are removed from the system and their airspace treated as inaccessible. The function ϕ is known to all participants beforehand and informs how they choose to route flights within their airspace.

However, the costs of routing a flight may be different than what is predicted beforehand. The profit-sharing mechanism may not account for delays due to weather, or airspace closures. We write the actual incurred cost as $c^{f'}$, as opposed to the predicted cost c^f that was used to calculate ϕ^f. This translates to $u^{f'}, v^{f'}$ for the actual revenue and profit, where we assume $u^{f'} = u^f$ and $v^{f'} = u^{f'} - c^{f'}$. To correct for those costs, a reimbursement rule φ_j is defined such that $\varphi_j(S, v^f, v^{f'}) = \varphi_j^f = \rho_j(\phi^f, j)\phi_j^f + c_j^{f'}$ is the total amount paid to sector (or SP) j by the airspace system after completion of the flight. This reimburses the SP for the costs it incurs for the flight, and then rewards it with a profit $\rho_j(\phi^f, j)\phi_j^f$, where $\rho_j : \phi^f, \mathcal{S} \to \mathbb{R}$. We will always assume that $u^{f,\prime} = u^f$, and will assume $c^{f,\prime} = c^f, v^{f'} = v^f$ for this work unless otherwise specified (e.g., in Theorem 2 below).

IV. Shapley Profit-Sharing Mechanism

The Shapley value was first described by Lloyd Shapley in [13]. A foundational concept in cooperative game theory, it divides the value obtained by a collection of agents in a manner that satisfies several desirable properties. We then prove that a profit-sharing mechanism $\phi(\mathcal{S}, v)$ based on the Shapley value has a positive outcome for the airspace system; specifically, all SPs are incentivized to route flights along their globally optimal path.

A. Desired Properties

We would like the profit-sharing mechanism $\phi(\mathcal{S}, v) = \{\phi_1, \ldots, \phi_n\}$ to have several desirable properties:

1) **Efficiency**: $\sum_{j\in\mathcal{S}}\phi_j(\mathcal{S}, v) = v(\mathcal{S})$.
The sum of the profit earned of individual agents equals the total profit earned for all agents. Efficiency ensures that the system distributes exactly as much value as it receives.

2) **Symmetry**: $v(S \cup \{i\}) = v(S \cup \{j\})\ \forall i, j \in \mathcal{S}, S \subseteq \mathcal{S} \setminus \{i, j\} \Rightarrow \phi_i(\mathcal{S}, v) = \phi_j(\mathcal{S}, v)$.
If the marginal contributions of sector i and sector j to all subsets of sectors not including either sector i or sector j are identical, then the shares of profits awarded to the two sectors are identical. Symmetry ensures that all agents with the same marginal contribution are treated equally.

3) **Dummy**: $\Delta_j(v, S) = 0\ \forall S \subseteq \mathcal{S} \Rightarrow \phi_j(\mathcal{S}, v) = 0$.
An agent that does not add any value to any coalition is allocated a profit share of zero. This property ensures that if an agent does not contribute to the system, it does not receive anything from the profit-sharing mechanism.

4) **Strong Monotonicity**: $\Delta_j(v, \mathcal{S}) \geq \Delta_j(w, \mathcal{S}) \Rightarrow \phi_j(\mathcal{S}, v) \geq \phi_j(\mathcal{S}, w)$.
Strong monotonicity specifies that the greater the marginal contribution of an SP to all sectors, the higher should be its profit.

5) **Fairness** : $\phi_j(\mathcal{S}, v) - \phi_j(\mathcal{S} \setminus \{i\}, v) = \phi_i(\mathcal{S}, v) - \phi_i(\mathcal{S} \setminus \{j\}, v)$.
The fairness property says that for any two sectors i, j, the contribution of provider i to the profit of j is equal to the contribution of j to the profit of i. This is a "balanced contribution" property [12,29].

6) **Additivity**: $\phi_j(\mathcal{S}, v + w) = \phi_j(\mathcal{S}, v) + \phi_j(\mathcal{S}, w)\ \forall j \in \mathcal{S}$.
Additivity states that if we have two value functions v, w, we can find the Shapley values under a new value function $v + w$ by simply adding up the Shapley values of the original functions.

B. Shapley Profit-Sharing Mechanism

The Shapley value represents the average marginal contribution of an agent to a set of agents and is the *unique* function satisfying the properties above [13,30,31]. We now show its computation and application to our AAM domain.

Let Π be the set of all permutations of sectors in $\mathcal{S}$; as such, $|\Pi| = |\mathcal{S}|!$. $\pi \in \Pi$ is one possible permutation, for example $(3, 2, 5, \ldots)$. To find the average *marginal* contribution of a sector j, let $P(\pi, j)$ be the set of sectors that strictly precede sector j in permutation π; in the previous example, $P(\pi, 5) = \{3, 2\}$. Note that $j \notin P(\pi, j)\ \forall \pi \in \Pi, j \in \mathcal{S}$ and that $P(\pi, j) = \varnothing$ if and only if j is the first sector in π. Then, the Shapley value of sector j is given by

$$\begin{aligned}\phi_j(\mathcal{S}, v) &= \frac{1}{|\mathcal{S}|!}\sum_{\pi\in\Pi} v(P(\pi, j) \cup \{j\}) - v(P(\pi, j)) \\ &= \frac{1}{|\mathcal{S}|!}\sum_{\pi\in\Pi}\Delta_j(v, P(\pi, j))\end{aligned} \tag{5}$$

By substituting v^f for v, we have the Shapley value for a flight f. We occasionally overload notation by using $\phi_j(\mathcal{S}, v^f, R^f)$ to represent the Shapley value when flight f is limited to a particular set of routes R^f [see Eq. (4)]. To get ϕ_j^f, we specify a reimbursement mechanism φ_j^f. We first reimburse every sector (every SP's) actual costs for $c_j^{f'}$, and then split the actual profit $v^{f'} = u^{f'} - c^{f'}$ based on each sector's Shapley value. Thus,

$$\varphi_j(\mathcal{S}, v^f, v^{f'}) = \frac{\phi_j(\mathcal{S}, v^f)}{\sum_{l\in\mathcal{S}}\phi_l(\mathcal{S}, v^f)} v^{f'}(\mathcal{S}) + c_j^{f'} \tag{6}$$

This assumes that SPs truthfully report their costs; Sec. VII.A.1 discusses how this may be possible. Note that in this case $\rho_j(\phi^f, j) = \frac{\phi_j(\mathcal{S}, v^f)}{\sum_{l\in\mathcal{S}}\phi_l(\mathcal{S}, v^f)} = \frac{\phi_j(\mathcal{S}, v^f)}{v(\mathcal{S})}$. If we follow the assumption made at the end of Sec. III.B that $u^f = u^{f'}, c = c^{f'}$, then $u^{f'} - c^{f'} = v^{f'} = v^f$ and this reimbursement mechanism reduces to $\varphi_j^f = \phi_j^f$. If $c^{f'} \neq c^f$ the desired properties introduced in Sec. IV.A still hold, because we can show $\varphi_j(\mathcal{S}, v^f, v^{f'}) = \phi_j(\mathcal{S}, v^f)\frac{v^{f'}}{v^f}\ \forall j \in \mathcal{S}$, which means every ϕ_j^f is scaled by the same ratio of actual profit over profit. In the remainder of Sec. IV, we will drop the superscript f notation and assume we are considering the cost, profit, etc. for a single flight, unless otherwise specified.

We demonstrate the computation of the Shapley value using the example in Fig. 2. Here, we have 4 sectors, given by $\mathcal{S} = \{1, 2, 3, 4\}$, with a flight with origin $o \in S_1$ at $(-1, 2)$ and destination $d \in S_4$ at $(2, -1)$. We use the revenue and cost functions modeled in Sec. III.A. In Fig. 2, the revenues $u(\{1, 2, 4\}) = u(\{1, 3, 4\}) = u(\{1, 2, 3, 4\}) = 6\sqrt{2}$ are equal, while the revenue of a coalition like $u(\{1, 4\}) = 0$ because no route connecting the origin and destination exists. The costs for different coalitions and routes are different: $c(\{1,2,4\},\text{optimal}) = 3\sqrt{2}$, $c(\{1,2,4\},\text{hot}) = 1 + \sqrt{5} + \sqrt{2}$, $c(\{1,2,3,4\},\text{alternative}) = c(\{1,3,4\},\text{optimal}) = 4 + \sqrt{2}$. Note that the alternative route for coalition $\{1, 2, 3, 4\}$ is the optimal route for coalition $\{1, 3, 4\}$, but not for the overall airspace $\mathcal{S}$.

We now reason through the computation of the Shapley value for a single sector, for example, sector 2. The marginal contribution of sector 2 in an ordering π is positive if and only if its inclusion enables a route with greater profit than can be constructed with a coalition of sectors preceding it in π, $P(\pi, 2)$. For example, in the permutation $(1, 4, 2, 3)$, sectors 1 and 4 alone do not provide a path between the origin and destination, so the formation of a valid route constitutes a marginal contribution by sector 2. In another ordering $(1, 4, 3, 2)$,

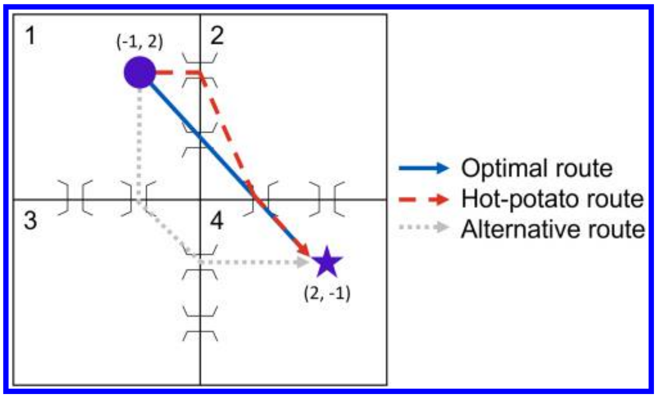

Fig. 2 Three routes are shown: the *optimal* route in solid blue, the *hot-potato* route in dashed red, and an *alternative* route in dotted gray.

while sectors 1, 4, and 3 provide a contiguous path (the *alternative* route in Fig. 2), sector 2 enables a lower cost, higher profit route (the *optimal* route in Fig. 2) and thus provides a marginal contribution equal to the increase in profit.

A full table calculating the Shapley value for each agent is shown in Table A1 in Appendix A. Sectors 1 and 4 have a higher Shapley value because they contain the origin and destination locations for the flight. A successful coalition cannot form without both of these sectors, so they take a higher fraction of the profit. Sector 2 has a slightly greater value than sector 3 because it provides a shorter route.

To compute the Shapley value, we use a modified version of the DFS-SHAPLEY algorithm [32]. This method enumerates all connected induced subgraphs (in our setting, connected coalitions of sectors) and then calculates the Shapley value for every subgraph. We modify the algorithm to account for the value of all coalitions because [32] only calculates the value of connected coalitions. Nonconnected coalitions, while having no value in the original work, could have value in our setting because a path from the origin to the destination could still exist among some connected nodes. This is done by using the "stars and bars" combinatorics technique, removing some of the difference terms in the algorithm, and iterating through all origin and destination points within the value function.

C. Benefits of the Shapley Mechanism

We can show that implementing the Shapley profit-sharing mechanism in Eq. (5) has several important properties. It incentivizes SPs to 1) route flights along the globally optimal path and 2) increase interconnection between sectors [12].

First, we prove that SPs will route flights along the globally optimal path. Recall that $R(S)$ is the set of routes possible for a coalition S. We define the set of optimal routes as

$$R^*(S) = \{r | v(S, r) = \sup_{r' \in R(S)} v(S, r')\} \qquad \forall S \in \mathcal{S} \tag{7}$$

We now discuss the routing strategy that determines each route segment r_i. A route is divided into an ego segment r_i, and all other segments $r_{-i} = r \setminus \{r_i\}$. We define the concatenation of two route segments (or sets of route segments) as $r_i \oplus r_j$, e.g., a route can be defined by the ego segment r_i and all other segments r_{-i} such that $r = r_i \oplus r_{-i}$. Suppose sector j is in control of and determines r_i. We will define the set of possible route segments as

$$R_i(S) = \{r_i | r_i \in r \in R(S), r_i \in S_j\} \tag{8}$$

Let the routing strategy for each segment $r_i \in S_j$ be a mapping $\boldsymbol{R}_i : S, r_{-i} \mapsto r_i$. Here, the sector j determines what route segment r_i a flight will take while under sector j's control, given the coalition S and the route segments determined by other sectors r_{-i}. The other route segments r_{-i} determine where a flight enters sector j; the coalition S determines where the sector can send the flight next to continue its route. The concatenation of routing strategies for every segment forms a complete route: $r = \boldsymbol{R}_1(S, r_{-1}) \oplus \cdots \oplus \boldsymbol{R}_m(S, r_{-m})$, $r \in R(S)$ for arbitrary routing strategies $\boldsymbol{R}_1, \ldots, \boldsymbol{R}_m$. We will denote $\boldsymbol{R}_{-i}(S)$ as the routing strategies for the route segments r_{-i}.

We then define the optimal routing strategy $\boldsymbol{R}_i^*(S, r_{-i})$, which returns route segments that maximize the value of the completed route.

$$\boldsymbol{R}_i^* : S, r_{-i} \mapsto r_i^* \quad \text{s.t.} \quad v(S, r_i^* \oplus r_{-i}) = \sup_{r_i \in R_i(S)} v(S, r_i \oplus r_{-i}) \tag{9}$$

This is the set of route segments that maximize the overall value of a coalition $v(S)$. For brevity, we treat the r_{-i} as implied in the function definition for $\boldsymbol{R}_i$. We show that under the Shapley value profit-sharing mechanism, every SP earns the maximum profit by following $\boldsymbol{R}_i^*(S)$.

Theorem 1. For a given flight f, any coalition $S \subseteq \mathcal{S}$, and any other route segments r_{-i} chosen by other sectors, every coalition agent $j \in S$ with $r_i \in S_j$ maximizes their profit under the Shapley profit-sharing mechanism ϕ using the optimal routing strategy $\boldsymbol{R}_i^*(S)$. In other words, $\phi_j(\mathcal{S}, v, \boldsymbol{R}_i^*(S) \oplus \boldsymbol{R}_{-i}(S)) \geq \phi_j(\mathcal{S}, v, \boldsymbol{R}_i(S) \oplus \boldsymbol{R}_{-i}(S))$ $\forall \boldsymbol{R}_{-i}(S)$, for any $\boldsymbol{R}_i^*(S)$.

Proof. The maximum of ϕ_j occurs by maximizing the marginal value. That is,

$$\max_{\boldsymbol{R}_i} \phi_j(\mathcal{S}, v) = \max_{\boldsymbol{R}_i} \frac{1}{|\mathcal{S}|!} \sum_{\pi \in \Pi} \Delta_j(v, P(\pi, j)) = \frac{1}{|\mathcal{S}|!} \sum_{\pi \in \Pi} \max_{\boldsymbol{R}_i} \Delta_j(v, P(\pi, j)) \tag{10}$$

The max function can be pushed inside the summation because the routing strategy taken for every ordering $\pi \in \Pi$ is independent of other orderings.

With $P(\pi, j) = S$:

$$\Delta_j(v, S, \boldsymbol{R}_i^*(S) \oplus \boldsymbol{R}_{-i}(S)) = v(S \cup \{j\}, \boldsymbol{R}_i^*(S) \oplus \boldsymbol{R}_{-i}(S)) - v(S, \boldsymbol{R}_{-i}(S)) \geq v(S \cup \{j\}, \boldsymbol{R}_i(S) \oplus \boldsymbol{R}_{-i}(S)) - v(S, \boldsymbol{R}_{-i}(S)) = \Delta_j(v, S, \boldsymbol{R}_i(S) \oplus \boldsymbol{R}_{-i}(S)) \tag{11}$$

The first and third steps in Eq. (11) are the definitions of marginal value. The inequality of the second step is from the definition of $R_i^*(S)$ in Eq. (9). The Shapley value is solely dependent on the sum of marginal values, so an agent will maximize the Shapley value it gets by increasing its marginal value to the whole route (by minimizing routing costs). □

Theorem 1 holds for the grand coalition $\mathcal{S}$ because we proved it for all subsets $S \subseteq \mathcal{S}$. This theorem allows us to calculate the Shapley value before the flight (using instantaneous c) assuming that all SPs are using globally optimal routing.

Additionally, the optimal routing solution is a Nash equilibrium under the Shapley profit mechanism.

Corollary 1. Under the Shapley profit-sharing mechanism, every optimal routing strategy $\boldsymbol{R}_i^* \forall i \in \mathcal{S}$ is a Nash equilibrium.

Proof. Suppose that for some $r_i \in S_j$ for $j \in \mathcal{S}$, the routing strategy $\boldsymbol{R}_i^*$ is not a Nash equilibrium. Then the SP j would have an incentive to deviate and use a different strategy $\boldsymbol{R}_i$, where $\phi_j(\mathcal{S}, v, \boldsymbol{R}_i \oplus \boldsymbol{R}_{-i}^*) \geq \phi_j(\mathcal{S}, v, \boldsymbol{R}_i^* \oplus \boldsymbol{R}_{-i}^*)$. This contradicts Theorem 1. □

Now we can also show that globally optimal routing is robust to disruptions in the airspace that block the optimal route. More specifically, for all other sector routing strategies $\boldsymbol{R}_{-i}$ and a disruption limiting the route set to $R'(S) \subseteq R(S)$, SP j will choose the routing strategy that minimizes $c' \geq c$. Let us define $\boldsymbol{R}_i'(S) : S, r_{-i} \mapsto r_i' \in r' \in R'(S)$ as a routing strategy that limits the route segments to the subset of routes. Then let the optimal strategy be

$$\boldsymbol{R}_i'^* : S, r_{-i} \mapsto r_i'^* \quad \text{s.t.} \quad v(S, r_i'^* \oplus r_{-i}) = \sup_{r_i' \in R_i'(S)} v(S, r_i' \oplus r_{-i}) \tag{12}$$

Theorem 2. Assume $\phi_j(\mathcal{S}, v) \forall j \in \mathcal{S}$ is precomputed before flight, and during the flight the set of available routes is limited to $R'(S) \subseteq R(S)$. For any routing strategy $\boldsymbol{R}_{-i}$ and any coalition $S \subseteq \mathcal{S}$, every coalition agent $j \in \mathcal{S}$ with $r_i \in S_j$ maximizes their profit under the Shapley profit-sharing mechanism using routing strategy $\boldsymbol{R}_i'^*(S)$ for segment r_i over the limited route set.

Proof. The final profit an SP receives is

$$\varphi_j(\mathcal{S}, v, v') - c_j' = \frac{\phi_j(\mathcal{S}, v)}{\sum_{l \in \mathcal{S}} \phi_l(\mathcal{S}, v)} v'(\mathcal{S}) + c_j' - c_j' = \frac{\phi_j(\mathcal{S}, v)}{\sum_{l \in \mathcal{S}} \phi_l(\mathcal{S}, v)} v'(\mathcal{S}) \tag{13}$$

We would like to find the routing strategy that maximizes the actual profit over the routing strategies $\boldsymbol{R}'(\mathcal{S})$:

$$\arg\ \max_{\boldsymbol{R}_i'(\mathcal{S})} \frac{\phi_j(\mathcal{S}, v)}{\sum_{l\in\mathcal{S}} \phi_l(\mathcal{S}, v)} v'(\mathcal{S}) = \arg\ \max_{\boldsymbol{R}_i'(\mathcal{S})} v'(\mathcal{S}) = \boldsymbol{R}_i'^{*}(\mathcal{S}) \tag{14}$$

We can use Eq. (12) to substitute in $\boldsymbol{R}_i'^{*}$ on the last line. □

If air traffic is affected by weather or service disruptions, forcing the rerouting of flights along suboptimal routes, Theorem 2 shows that SPs will route around these disruptions as close to optimal as possible (e.g., in Fig. 2, if sector 2 is closed, the coalition (1, 3, 4) will take the gray route). These results assume a truthful and accurate measurement of c', which is discussed further in Sec. VII.A.1. Theorem 2 may also hold even without the Shapley value, which is discussed in Sec. VII.A.2.

Because SPs are encouraged to route optimally, they are incentivized to interconnect with other SPs as much as possible to find shorter routes. We now prove that the Shapley profit-sharing mechanism encourages SPs to interconnect with each other. Assume that a new set of routes $R^+(S)$ is provided, generated by new gates between sectors or the opening of previously closed airspace. We define the extended route set $\tilde{R}(S) = R(S) \cup R^+(S)$, and the routing strategy over the extended routes for route segment i as $\tilde{\boldsymbol{R}}_i(S)$ and over the extra routes as $\boldsymbol{R}_i^+(S)$. All SPs will prefer to optimize over the extended route set because it may contain more optimal routes.

Theorem 3. Given a set of original routes $R(S)$ and an extended route set $\tilde{R}(S) = R(S) \cup R^+(S)$, SPs maximize their profit by strategizing over the extended route set, $\phi_j(\mathcal{S}, v, \tilde{\boldsymbol{R}}_i^*(S) \cup \boldsymbol{R}_{-i}(S)) \geq \phi_j(\mathcal{S}, v, \boldsymbol{R}_i^*(S) \cup \boldsymbol{R}_{-i}(S))$ for segment $r_i \in S_j$.

Proof.

$$\begin{aligned}\Delta_j(v, S, \tilde{\boldsymbol{R}}_i^*(S) \cup \boldsymbol{R}_{-i}(S)) = \max\{&\Delta_j(v, S, \boldsymbol{R}^{+*}_i(S) \cup \boldsymbol{R}_{-i}(S)),\\ &\Delta_j(v, S, \boldsymbol{R}_i^*(S) \cup \boldsymbol{R}_{-i}(S))\}\\ \geq\ &\Delta_j(v, S, \boldsymbol{R}_i^*(S) \cup \boldsymbol{R}_{-i}(S))\end{aligned} \tag{15}$$

□

This implies that, under the assumption that establishing new routes has no fixed costs, SPs should always seek out newer routes to interconnect with other SPs. These routes could be the result of more gates being added between sectors or for the elimination of discrete gates altogether to allow for flights to cross the sector boundaries at any point (equivalent to having infinitely many gates). A corollary here is that the grand coalition is stable and in the core:

Corollary 2. The grand coalition $\mathcal{S}$ is stable.

Proof. Take a coalition $S \in \mathcal{S}$. This enables a set of routes $R(S)$. For all SPs $\tilde{j} \in \mathcal{S}\backslash S$, $R(S \cup \{\tilde{j}\})$ is an extended route set of $R(S)$—that is, $|R(S \cup \{\tilde{j}\})| \geq |R(S)|$. By Theorem 3, every coalition member $j \in S$ will benefit from the addition of $\tilde{j}$ to S. □

V. Results

In this section, we experimentally demonstrate the effectiveness of the Shapley value in encouraging optimal routing. The profits of different SPs are calculated by summing the profits over all the flights. We compare optimal routing and hot-potato routing strategies under several profit- and revenue-sharing mechanisms to the Shapley value mechanism and show that, under other mechanisms, SPs do not uniformly earn more profit using optimal rather than hot-potato routing. This implies that, under other mechanisms, some SPs are incentivized to send flights on inefficient routes. In this section, while $u^f = u^{f'}$ it may be possible that $c^{f'} \neq c^f$ especially under hot-potato routing, as SPs try to minimize their own routing cost $c_j^{f'}$. We first describe other revenue and profit-sharing mechanisms, illustrate the routing strategies used, and then show our experimental results.

A. Other Profit-Sharing Mechanisms

We defined the Shapley profit-sharing mechanism earlier in Eq. (5), which works as follows:

$$\begin{aligned}\phi_j^{f,\text{shapley}}(\mathcal{S}, v^f) &= \frac{1}{|\mathcal{S}|!} \sum_{\pi\in\Pi} v^f(P(\pi, j) \cup \{j\}) - v^f(P(\pi, j))\\ \varphi_j^{f,\text{shapley}}(\mathcal{S}, v^f, v^{f'}) &= \frac{\phi_j^f(\mathcal{S}, v^f)}{v^f(\mathcal{S})} v^{f'}(\mathcal{S}) + c_j^{f'}\end{aligned} \tag{16}$$

We will compare it to two other possible sharing mechanisms. First, we compare it against the *sender-keep-all* profit-sharing mechanism discussed in Sec. II. This mechanism gives all the revenue earned from a flight to the originating SP:

$$\begin{aligned}\phi_j^{f,\text{senderkeep}}(\mathcal{S}, v^f) &= \begin{cases} u^{f'}(\mathcal{S}) - c_j^{f'}, & \text{if } o \in S_j\\ -c_j^{f'}, & \text{otherwise}\end{cases}\\ \varphi_j^{f,\text{senderkeep}}(\mathcal{S}, v^f, v^{f'}) &= \begin{cases} u^{f'}(\mathcal{S}), & \text{if } o \in S_j\\ 0, & \text{otherwise}\end{cases}\end{aligned} \tag{17}$$

We also test a proportional *revenue*-sharing mechanism that divides the revenue among all SPs that would carry the flight on the optimal route in proportion to the distance traveled within each SP. We assume that only one optimal route exists. Let $d_j^f = \sum_{r_i^f\in S_j} \|r_i^f\|_2$ be the portion of the optimal route in sector j, so that $\sum_{j\in\mathcal{S}} d_j^f = \sum_{r_i^f\in r^{f*}\in R^{f*}(S)} \|r_i^f\|_2$. Then,

$$\begin{aligned}\phi_j^{f,\text{revenue}}(\mathcal{S}, v^f) &= \begin{cases} \frac{d_j^f}{\sum d_j^f} u^{f'}(\mathcal{S}) - c_j^{f'}, & \text{if} \exists r_i^f \in R^{f*}(\mathcal{S}) \text{ s.t. } r_i^f \in S_j\\ -c_j^{f'}, & \text{otherwise}\end{cases}\\ \varphi_i^{f,\text{revenue}}(\mathcal{S}, v^f, v^{f'}) &= \begin{cases} \frac{d_j^f}{\sum d_j^f} u^{f'}(\mathcal{S}), & \text{if} \exists r_i^f \in R^{f*}(\mathcal{S}) \text{ s.t. } r_i^f \in S_j\\ 0, & \text{otherwise}\end{cases}\end{aligned} \tag{18}$$

The revenue-sharing mechanism is based on the optimal route between the origin and destination, not the actual route taken. If sharing were based on the actual route, some SPs could use side payments to influence other SPs into directing traffic towards them, similar to the current bilateral agreements explained in Sec. II.

B. Routing Strategies

We compare optimal routing to hot-potato routing in the following experiments. Routing strategies define how an SP decides the routes $r_i^f \in S_j$ that it controls. For optimal routing, the routes chosen by S_j are the globally optimal route segments, which is $\boldsymbol{R}_i^{f*}(\mathcal{S})$ for $r_i^f \in S_j$.

$$\boldsymbol{R}_i^{f,\text{opt}}(\mathcal{S}) = \{r_i^f \mid r_i^f \in r^{f*} \in R^{f*}(\mathcal{S})\} \tag{19}$$

Under hot-potato routing, sectors send their flights along the route that minimizes their own costs ($\arg\ \min c_j^f(r_i^f)$), while moving the flight closer to the target (the constraint $\|d - w_i^f\|_2 < \|d - w_{i-1}^f\|_2$, where d is the destination of the flight). This minimizes costs for the SP, but is not globally efficient and could lead to higher costs for other SPs.

$$\boldsymbol{R}_i^{f,\text{hot}}(\mathcal{S}) = \{\arg\ \min_{r_i^f} c_j^f(r_i^f) \mid \|d - w_i^f\|_2 < \|d - w_{i-1}^f\|_2\} \tag{20}$$

C. Independent Sector Results

In this section, we present simulation results where different profit-sharing mechanisms split profit from flights among SPs using either globally optimal or hot-potato routing. We measure profit earned per SP (in dollars) and total distance traveled by all flights in the scenario (a measure of efficiency, in kilometers). The airspace is structured as described in Fig. 1, with four 3 km-by-3 km square sectors with connecting gates separated by 1 km arrayed in a grid. This is done over four different simulation scenarios, with varying characteristics:

1) *Random traffic scenario*: Each SP sends 20 flights to every other SP. A total of $12 \times 20 = 240$ flights are sent. This serves as a benchmark scenario where the average effects of the Shapley value and routing decisions can be studied.

2) *Special traffic scenario*: SP 1 sends 20 flights to destinations in SP 4, and vice versa. SP 2 sends 10 flights to destinations within its sector, while SP 3 sends and receives no flights, receiving profit only through participation in the system. This scenario demonstrates the SP profit under a diverse traffic flow pattern. A total of $2 \times 20 + 10 = 50$ flights are sent.

3) *1-Only traffic scenario*: SP 1 sends 20 flights to destinations in SPs 2, 3, and 4. No other flights are sent or received. This scenario illustrates the disparity in profits under a very imbalanced traffic flow pattern. A total of $3 \times 20 = 60$ flights are sent.

4) *Uneven traffic scenario*: SP 3 controls the merged bottom two sectors (with the border separating SPs 3 and 4 in Fig. 1 removed). SPs 1, 2, and 3 each send 20 flights to destinations in every other SP and 10 flights to destinations within itself. This scenario studies the outcome when the area controlled by an SP is not even. A total of $6 \times 20 + 3 \times 10 = 150$ flights are sent.

The results are presented in Fig. 3. The first column shows actual profit by SP $\frac{1}{|\mathcal{F}|}\sum_{f\in\mathcal{F}}(\varphi_j^f - c_j^{f\prime})$ for each combination of mechanism and routing method, the second column compares average flight distance when all SPs use either optimal or hot-potato routing $\frac{1}{\mathcal{F}}\sum_{f\in\mathcal{F}}\sum_{r_i^f\in r^f}\|r_i^f\|_2$, and the third and fourth columns visualize the routes taken under optimal and hot-potato routing, respectively. Profit per SP is compared for every combination of profit-sharing mechanism and routing method. Under the Shapley profit-sharing mechanism, every SP earns more profit by using the optimal routing method as compared to the hot-potato routing method. By contrast, in some scenarios under the sender-keep-all or revenue-sharing mechanisms, some SPs prefer hot-potato routing while others prefer optimal routing.

For example, in the *Special* scenario with sender-keep-all and revenue-sharing mechanisms, SPs 2 and 3 earn more profit under hot-potato routing, while SP 1 and 4 earn more (or lose less) under optimal routing. The difference in profit means that globally optimal routing is not a Nash equilibrium and that flights will be directed on a less efficient route. These differences are due to the imbalance of traffic flows in some scenarios. While we do not see this behavior in the *Uniform* scenario where traffic flows are equal and costs are

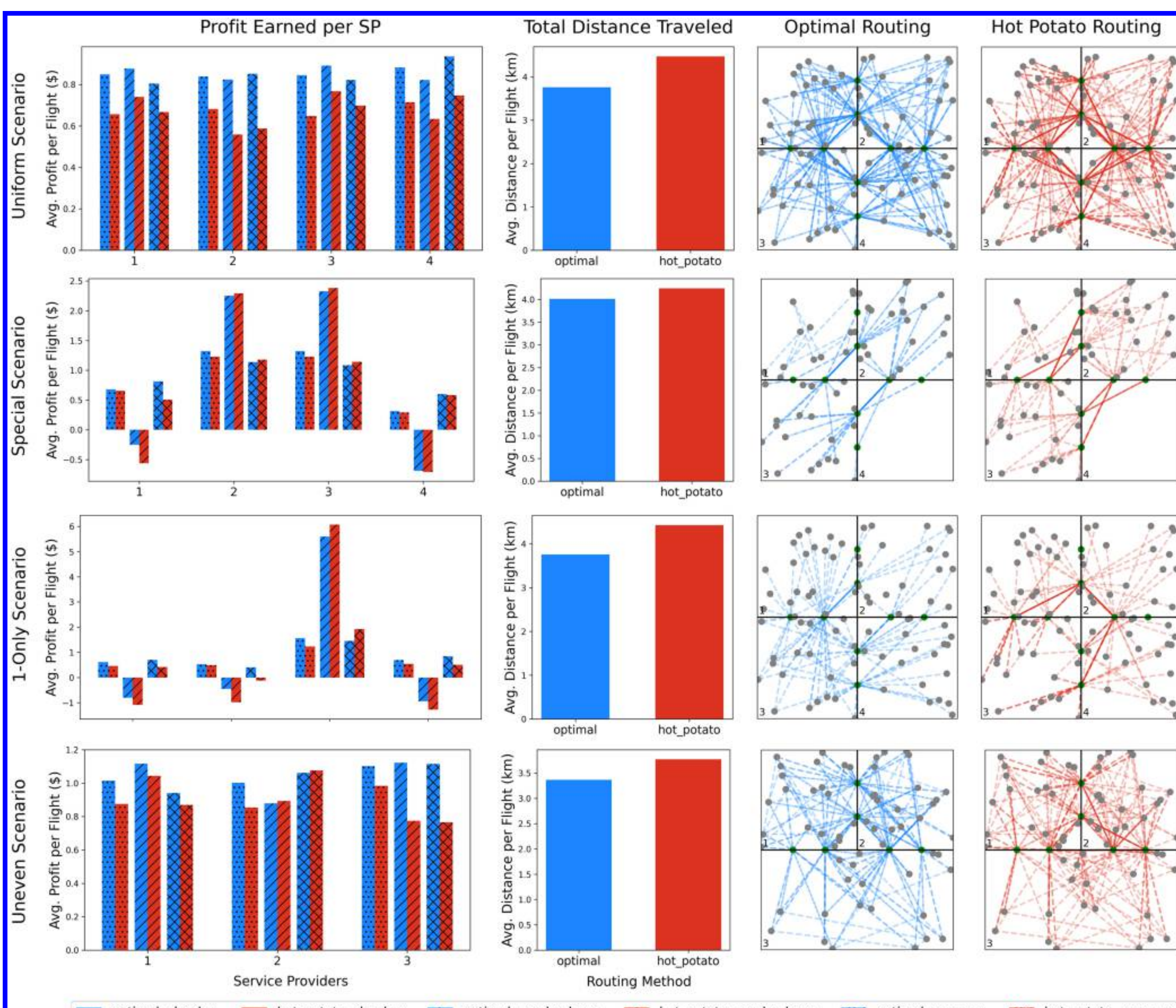

Fig. 3 Average profit per flight per SP for different methods, average distance per flight, and routes traversed in optimal and hot-potato routing for simulated traffic scenarios.

distributed evenly, any perturbation to the traffic demand or airspace structure leads to a possible divergence in the preferred routing strategy for non-Shapley value mechanisms, as shown in the *Special* and *1-Only* scenarios.

Optimal routing is socially preferred over hot-potato routing because of the minimization in distance traveled for flights. In the *Uniform* traffic scenario, we see that optimal routing improves profit by approximately 21% and decreases distance traveled by 16%. Hot-potato routing sometimes forces flights to take long detours to minimize cost to the SP—flights from SP 1 to 3 originating close to the boundary between SP 1 and 2 are routed through SPs 2 and 4 to reach SP 3 because doing so minimizes the total cost for SP 1.

We also test the sensitivity of these results to the revenue function used. In Fig. B1 of Appendix B, we show that the Shapley profit-sharing mechanism incentivizes optimal routing even when the revenue function is varied.

VI. Allocations

In addition to the privatization of air traffic services for AAM, the FAA has stated that multiple operators should be able to manage flights in the same geographic area. This could prevent monopolies in sector markets, where operators can only contract with one SP for traffic services. A monopolistic SP, especially in a high-density area, could hinder innovation and growth of AAM operations.

In this section, we study the impact of assigning multiple (small) sectors to an SP and how that affects the profit earned under the Shapley profit-sharing mechanism for each SP. We provide one system of profit-sharing for flights and then show that an allocation method that assigns an equal number of sectors between two SPs still leads to significant differences in profit earned due to the structure of the airspace. Furthermore, different demand patterns also create differences in profit earned. At the end of the section, we propose some future directions of work for the allocation problem.

A. Multiple SPs for a Region

For multiple SPs to operate in a region, we use a method of *subdivisioning*. A single region (e.g., Boston) is divided into sectors (e.g., a neighborhood), with each SP having exclusive control of a set of sectors. Flights passing through to a new sector are handed off to the SP responsible for that sector. In this way, it is clear which SP has the responsibility for a flight's route through every step of its journey. Ultimately, the subdivisioning method attacks the problem of a monopoly SP by splitting regions into small enough sectors and allocating these sectors to SPs.

One downside of subdivisioning is that it creates many small sectors, which exponentially increases the runtime of calculating the Shapley value. Calculations of the Shapley value are necessary to determine the expected profit share for each SP ϕ_j under a given assignment of sectors to SPs $\mathcal{A}$. We find that our methods of calculating the Shapley value are sufficient for running offline computations on known origin–destination pairs. We can envision a process of the FAA process of portioning out subsectors to SPs like so:

1) Multiple SPs receive slots or rights to operate in a region (e.g., the Boston metropolitan region). This determines $\mathcal{P}$, the set of all SPs.

2) The FAA divides that region into sectors. This could be based on existing boundaries (e.g., Cambridge, Somerville, Newton, etc.), census data, data on AAM traffic patterns, regulatory considerations, and other data sources. This determines $\mathcal{S}$, the set of sectors composing the airspace network.

3) The FAA allocates sectors to different SPs through optimization, random assignment, auctions, or other methods. This could be done with knowledge of expected profit share, based on expected origin–destination pairs or demand. This step defines the allocation function $\mathcal{A}: \mathcal{S} \to \mathcal{P}$. This could be updated on a regular basis (e.g., annually or semi-annually) to ensure that imbalances in profit are averaged out. Here, we randomly assign an equal number of sectors to each SP to demonstrate that allocations of sectors are important and encourage future work on allocation methods.

4) The Shapley values for each pair of *(sector, origin–destination)* are calculated $\phi_j^f(\mathcal{S}, v)$, $j \in \mathcal{S}$. This implements a Shapley profit-sharing mechanism.

5) SPs manage flights that pass through the sectors they are responsible for. This process incurs costs for the SP and generates revenue and profit that is distributed through the Shapley profit-sharing mechanism. Reimbursements $\varphi_j(\mathcal{S}, v^f, v^{\text{fprime}})$, $j \in \mathcal{S}$ are distributed.

In this work, sectors are treated independently in the Shapley mechanism regardless of which SP has responsibility. The total profit an SP earns for a particular (o, d) is equal to the sum of the Shapley profits from the sectors it is responsible for:

$$\phi^k(\mathcal{S}, v^f) = \sum_{\mathcal{A}(j)=P_k} \phi_j(\mathcal{S}, v^f(\mathcal{S}, R^f)) \tag{21}$$

Corollary 3. For sectors $S_1, \ldots S_j$ controlled by service provider $P_k \in \mathcal{P}$, P_k is incentivized to route flights optimally using routing strategies $\boldsymbol{R}_i^{f*}$ for route segments r_i^f, where $r_i^f \in S_j, \mathcal{A}(j) = P_k$.

Proof. By Theorem 1, each SP P_k maximizes its profit for each route segment $r_i^f \in S_j, \mathcal{A}(j) = P_k$ by using the optimal strategy $\boldsymbol{R}_i^{f*}$. □

B. Impact of Allocations

In this section, we study the possible outcomes for different allocations $\mathcal{A}$. We show that, even under uniform demand, different allocations of sectors to SPs will have large variations in total profit for each SP due to the airspace structure. Our experiment proceeds as follows:

1) We construct an airspace network with a 3-by-4 grid of 1 km × 1 km sectors, with one gate on each side.

2) We place an origin/destination point at the center of each sector and then create a flight for every permutation of origin and destination ($12 \times 11 = 132$ origin–destination pairs, i.e., the set of flights $\mathcal{F}$). Using the Shapley profit-sharing mechanism, we find the profit share ϕ_j^f each sector receives for each flight.

3) We assume there are two SPs, red and blue. We test all $\frac{\binom{12}{6}}{2} = 462$ ways of allocating sectors to the two SPs (dividing by 2 due to symmetry). For each allocation, we follow the profit calculation in (21), sum profit over all origin–destination pairs OD, and compare the difference in profit as a fraction of total profit (the *relative difference*), $\frac{\phi^{\text{blue}} - \phi^{\text{red}}}{\phi^{\text{blue}} + \phi^{\text{red}}}$, where ϕ^{blue} (and ϕ^{red} similarly) is defined as

$$\phi^{\text{blue}} = \sum_{f \in \mathcal{F}} \phi^{\text{blue}}(\mathcal{S}, v^f) = \sum_{f \in \mathcal{F}} \sum_{\mathcal{A}(S_j)=\text{blue}} \phi_j(\mathcal{S}, v^f(\mathcal{S}, R^f)) \tag{22}$$

We plot the relative difference for every allocation in a histogram at the top left in Fig. 4. The average relative difference is $\mu_{\text{diff}} = -0.00216$ and the standard deviation is $\sigma_{\text{diff}} = 0.0436$. The asymmetry in the histogram is due to the routing algorithm using the first shortest path of multiple options and the fact that not all allocations are represented due to symmetry. The difference in profit between SPs can be up to 10% of the total profit earned by the SPs, solely due to the sectors assigned to each SP. This can be explained by the importance of the central sectors: If flight demand is uniform across the airspace, the shortest path for many flights will cross the central airspace sectors, and these sectors thus have a higher Shapley profit share. While most allocations have a relatively even split in profit, outlier allocations can create a sharp difference in total profits for SPs. This result is robust to the number of gates (which shortens the optimal route), as demonstrated in Appendix C.

The relative difference extends to (and is magnified by) irregularities in the airspace structure. We follow the above experimental procedure for a random airspace structure scenario, created by randomly selecting 14 points, and then defining sectors by the Voronoi cell generated by these points. The points serve as origin and destination locations.

The outcome in Fig. 5 shows an even greater distribution of relative differences. The average relative difference is $\mu_{\text{diff}} = -0.0003$, with the standard deviation $\sigma_{\text{diff}} = 0.082$. The irregularity in sector sizing magnifies the relative difference possible between SPs; for example,

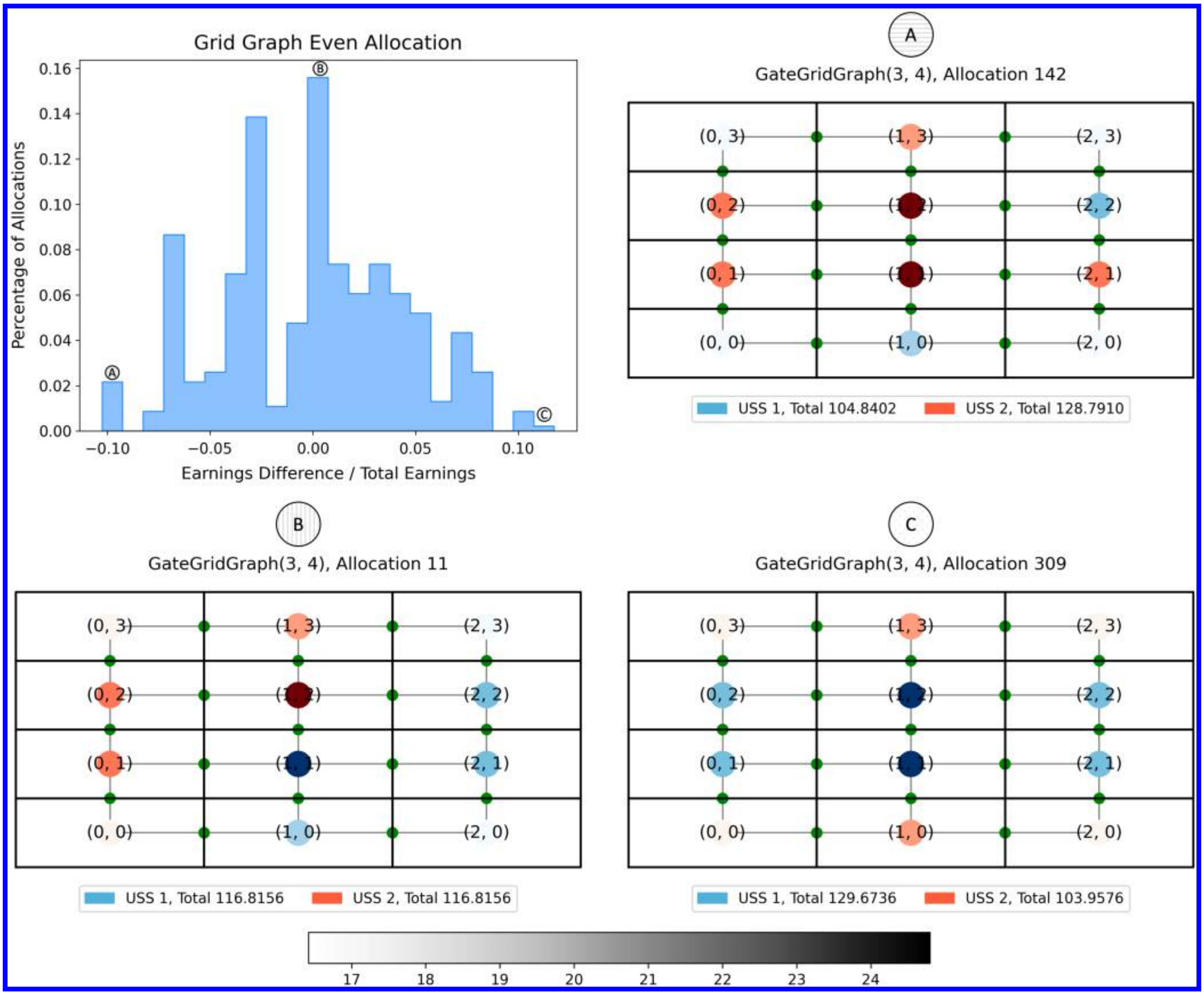

Fig. 4 Top left: relative difference in profits between 2 SPs. Three example allocations are shown, with lighter coloration indicating less earnings.

sectors 1 and 10 are very valuable in the example given, so if one SP is responsible for both of these sectors, it captures much more profit.

C. Impact of Demand

Different flight patterns can also create differences in total profits for SPs. We construct *random demand profiles* across the flights that simulate different demand for origin–destination pairs by weighing each flight by some amount. This is done by defining a random profile of weights $\lambda : f \mapsto [0, 1]$ that maps each origin–destination pair to a demand uniformly distributed between 0 and 1. Then, the total profit for one SP in the example given in Sec. VI.B is:

$$\phi^{\text{blue}} = \sum_{f \in \mathcal{F}} \sum_{\mathcal{A}(S_j)=\text{blue}} \lambda(f)\ \phi_j(\mathcal{S}, v^f(\mathcal{S}, R^f)) \tag{23}$$

We test 1,000 random demand profiles on a single even allocation and plot the relative difference defined in Sec. VI.B in Fig. 6.

Under uniform demand, where $\lambda(f) = 1\ \forall\ f \in \mathcal{F}$, the two SPs earn the same total profit under a balanced allocation like Allocation 11 (see Fig. 4). However, with a random demand profile, the profits of each SP diverge. For allocation 11 across all profiles, the average relative difference is $\mu_{\text{diff}} = 0.001$, while the standard deviation is $\sigma_{\text{diff}} = 0.031$.

D. Implications

The allocation of sectors to SPs has a significant impact on their profits due to the airspace network structure and flight demand. In our experiments, a 10% relative difference in allocations results in an approximately 20% difference in total profit between SPs. For established SPs, this affects company budgets and business growth prospects; it can also put fledgling companies out of business and lead to the early consolidation of SPs. Principled sector allocation processes need to therefore be developed. Examples of rule- and market-based methods in other contexts include spectrum allocation auctions for radio frequencies [33] and slot allocation rules for flights at airports [20].

VII. Discussion

We now outline the possible impacts of implementing profit-sharing based on the Shapley value among AAM SPs, and show a possible concept of operations on how the Shapley value method could integrate with AAM operations. We then discuss challenges in the emerging field of AAM traffic management and in traditional air traffic management generally, and how the Shapley value might help address or otherwise impact these problems.

A. Potential Impacts of Profit-Sharing Based on Shapley Value

1. Truthful Cost Reporting

Since profit computation takes as input the costs reported by SPs, a reasonable question involves incentives for the truthful reporting of incurred routing costs. Suppose an SP is compensated with $c_j' + \rho_j(\phi, j)(u' - c')$ in accordance with our scheme for a profit of $\rho_j(\phi, j)(u' - c')$, where $\rho_j(\phi, j) = \frac{\phi_j(\mathcal{S}, v)}{\sum_{i \in \mathcal{S}} \phi_i(\mathcal{S}, v)}$. Now, consider a

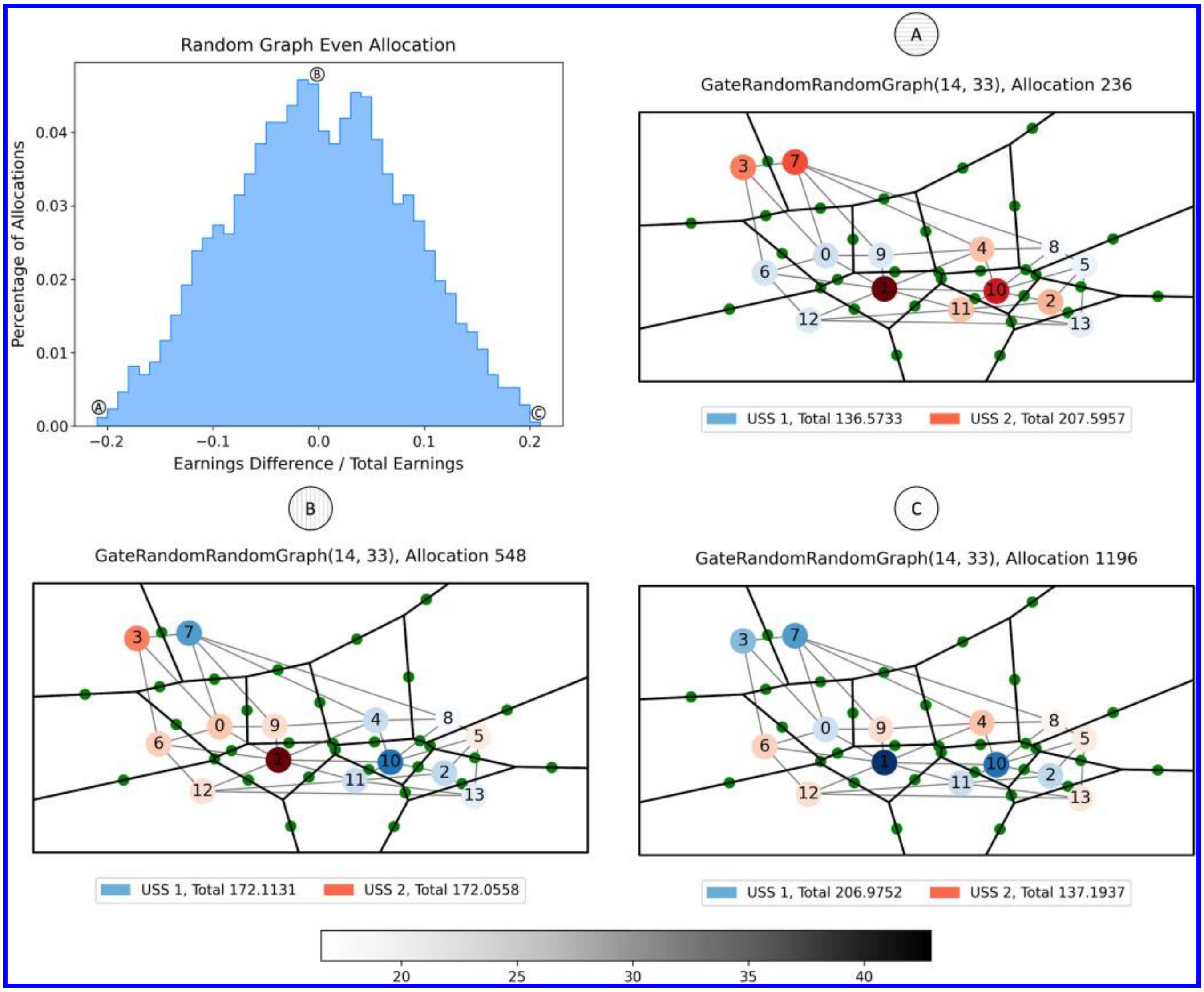

Fig. 5 Top left: relative difference in profits between 2 SPs. Three example allocations are shown.

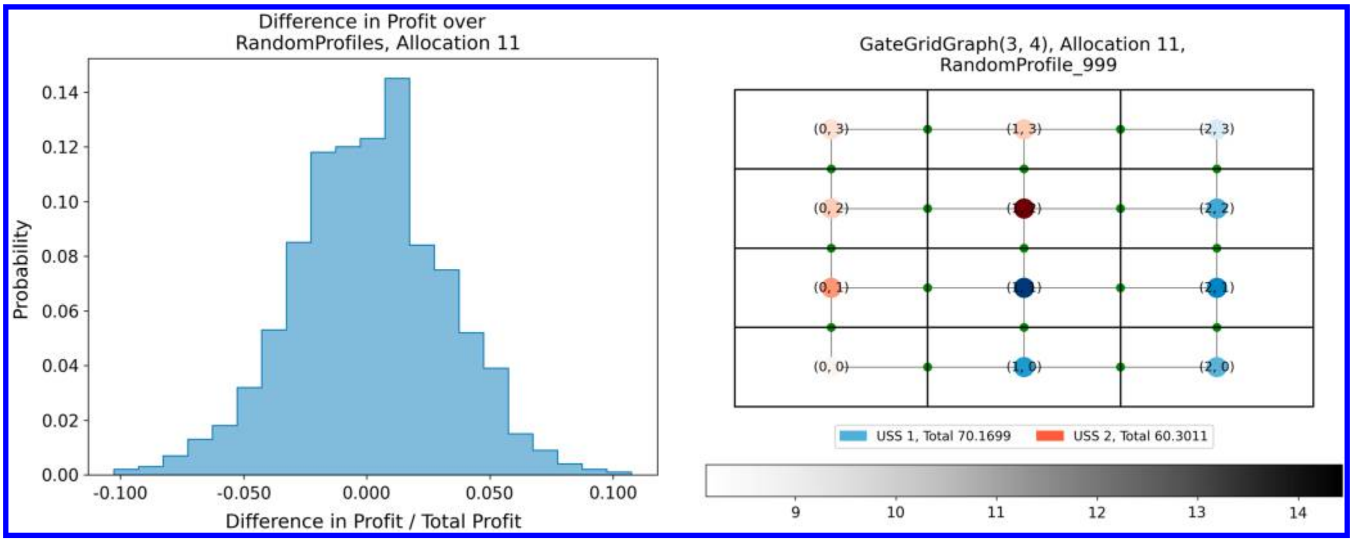

Fig. 6 Left: relative difference in profit over 1000 random profiles. Right: profits earned for each sector for a single random profile and allocation (relative difference 0.750).

situation in which the SP misreports its cost as δ_j more than its true routing cost. Its profit would then be $c'_j + \delta_j + \rho_j(u' - (c' + \delta_j) - c'_j = \delta_j + \rho_j(u' - c' - \delta_j) = \rho_j(u' - c') + \delta_j(1 - \rho_j)$, or an increase of $\delta_j(1 - \rho_j)$ over the original profit. Clearly, this is unacceptable—if all SPs attempted to game our system in this way, it could seem impossible to route a flight profitably.

However, in the aviation context, it is straightforward to track the actual route (and thus distance) traveled due to requirements such as ADS-B Out and remote identification for drones [34]. Then, one way to ensure truthful cost reporting is for the regulatory authority to assign a fixed cost per unit distance routed and to periodically update it based on changes in technology, economic conditions, or policy.

2. *Profit Share Determination*

While we have argued for the use of the Shapley value in determining profit share, it is not the only valid distribution. In fact, *any* profit-sharing mechanism with a positive allocation to all agents (i.e., SPs) along the route will incentivize optimal routing. This desirable property is inherent to any form of *profit* sharing; if we had used a revenue-sharing model instead, the guarantee would not hold.

To see why, we consider the common economic pie metaphor. Under a profit-sharing mechanism with fixed positive allocations, suboptimal routing will decrease the size of the pie. Therefore, all agents are incentivized to route optimally and, if optimal routing is impossible (e.g., due to congestion), to minimize any additional cost incurred. On the other hand, under revenue-sharing with fixed positive allocations, an agent will try to minimize its own cost to maximize its profit, i.e., by using hot-potato routing, because it will always receive the same revenue regardless of the route traveled.

While any profit-sharing mechanism can work, the selection of *which* participants have a nonzero allocation must be considered. If a participant that could provide an alternative route is not given an allocation, that participant will have no incentive to cooperate. This is particularly important when the system is congested and such alternative routes can relieve the congestion, which is enabled by the Shapley value. On the other hand, if a participant without any practical value is given an allocation, that participant becomes a free rider, benefiting without having to make any contribution. One approach to determine which participants are allocated a share leverages the concept of *spatial locality*, which we discuss next.

3. *Spatial Locality*

One potential concern with using the Shapley value for computing profit share involves geographic proximity. It is possible for an SP extremely far removed from the actual area of service to nevertheless receive a small share of profit. For example, a poor choice of value function to compute the Shapley values, such as a binary function that values every coalition that creates a path as 1 (a revenue-sharing method), can result in such counter-intuitive allocations. However, this type of behavior disappears when we use the value function based on the *profit* accrued by a coalition of SPs, which we have done in this work. At a certain point, routing through an SP far away from the shortest path generates a negative marginal contribution (negative profit), which turns it into a dummy agent that receives no share of the profit by the properties from Sec. IV.A.

B. Operation of AAM

The Shapley value method outlined in Sec. IV was designed for AAM operations, but we have not yet specified how such a method would realistically function. In this section, we outline a concept of operations for the strategic management of AAM flights in a future where SPs use and are regulated under the Shapley value method.

1) SPs bid for and/or are assigned sectors in a region by the airspace authority for a certain period of time (e.g., sectors in the New York City region by the FAA for a year). The airspace authority also sets an SP operational cost per mile, based on feedback from SPs and its own determination.

2) Based on the sector assignments and costs, the profit fraction to each SP for an origin–destination pair is calculated for many (ideally all) possible origin–destination pairs in a central and transparent fashion to all SPs. This establishes the optimal routes that flights will take under nominal conditions. While this calculation may take a long time (especially if there are many pairs considered), it can be done offline once and implemented before any flights are flown, as long as the calculation time is less than the period of time SPs hold their sector assignment for (e.g., a month of runtime vs a year of sector assignments).

3) Once the profit fractions for each route are established, we can now consider a flight going from an origin to a destination. The flight contracts with the origin SP in charge of the area in an on-demand fashion and agrees to a lump-sum cost. The origin SP then coordinates with other SPs and sets a trajectory based on each SP's feedback; the trajectory selected will be as globally optimal as possible when accounting for strategic traffic management to maximize profit.

4) The flight travels along the selected trajectory to its destination, with deviations as needed based on tactical considerations and congestion concerns. Location tracking by different services, including but not limited to SPs, is published to the central servers of the airspace authority and corroborated by government data (e.g., the FAA's Flight Information Management System [3]). This data reports the distance traveled and thus determines the actual incurred costs of managing that flight. This does require that AAM flights be tracked throughout their flight, which is done through systems like Remote ID [3].

5) The revenue and costs are finally divided among the SPs using the Shapley value method described in this paper.

This process would be repeated as needed, based on the period a sector allocation lasts (in this example, a year). Periodic changes to sector ownership, origin/destination, and costs would account for changes in AAM technology and market conditions. Future work could continue to refine and build on this concept of operations.

C. Future Work

This paper represents a first step in developing a market structure for AAM traffic management SPs. We now discuss several areas of future work needed to develop effective AAM traffic management techniques. In these discussions, we assume that the Shapley value can provide incentive-based profit-sharing solutions that encourage a baseline level of cooperation among different SPs. However, there remain unaddressed challenges that may require further study and even changes to the regulatory landscape for AAM.

1. *Interaction with Intra-SP Traffic Management*

In this work, we abstract away congestion management within an SP and assume that flights do not conflict. In a real airspace system, SPs may treat flights transiting their sector differently depending on the fraction of profit they earn, and inter-SP coordination could be affected by internal SP traffic management methods, whether protocol-based or through centralized optimization [23,35,36]. A preliminary study suggests that using the Shapley value for congestion management in an airspace system does not significantly affect performance, regardless of the traffic management methods used within a sector. This deprioritization can be tolerable because, without the Shapley value, SPs that do not receive any benefit from a flight would have no incentive to ever carry that flight, forcing a regulatory solution that would have to specify complex rules around SPs assisting each other instead of a more flexible, incentive-driven solution.

2. *Impact for ANSPs in Europe*

The Shapley value method described in our paper can also be used for aligning incentives in current air traffic control systems, where private ANSPs must coordinate the management of flights across geographical areas. For example, the European airspace consists of many public-private ANSPs with geographical monopolies that, while unified under EUROCONTROL, have some control over their pricing and routing policies. This leads to pricing differences, to the extent that up to 6% of flights detour from the shortest route available in favor of one that avoids higher route surcharges [37].

The Shapley value method could incentivize better collaboration between ANSPs in several ways. For example, as discussed previously, a Shapley value method necessitates that SPs agree on a common measure of costs and are particularly sensitive to cost misreporting. If there is a pre-existing framework of cooperation, like in EUROCONTROL, it is easier to agree on a common cost measure and use the existing framework to manage cost misreporting. Additionally, if an SP reports its costs higher than other SPs, it contributes less marginal contribution to each coalition it joins, which means its profit share will be correspondingly lower. Future research can leverage data from the European airspace to examine the impact of a Shapley value method in the context of current air traffic management practices.

3. Net Neutrality-Type Challenges in AAM

In the context of the Internet, net neutrality refers to the notion that Internet SPs should treat all content equally, without favoring one content creator or type of content over another. This has become a complex ethical and economic question in Internet policy, with companies picking sides in the debate based on their business models and affiliations. In many instances, ISPs that also produce content will give preference to data from an affiliated content creator rather than a competing content creator. An analogous situation in the AAM context would be when an SP is also an aircraft operator.

The FAA has explicitly stated that entities that are aircraft operators may also be SPs [3]. Consequently, a single entity may serve as both an operator of flights and an SP for other aircraft operators. This dual role as both aircraft operator and SP is analogous to an ISP also being a content creator, with the physical airspace being analogous to capacity-constrained bandwidth. It remains to be studied how different regulatory policies (e.g., similar to ones that try to ensure equal treatment of all aircraft operators) might affect AAM traffic operations. These are some of the open questions that need to be resolved before the full potential of advanced aerial mobility can be realized in practice [10].

VIII. Conclusions

With the vast emerging market for advanced air mobility, private third-party SPs are expected to provide traffic management services. Drawing lessons from ISPs, we propose a profit-sharing mechanism based on the Shapley value. The proposed mechanism encourages cooperation among SPs and routes flights on their globally optimal paths, regardless of individual costs. In addition to optimal routing, it incentivizes AAM traffic management SPs to cooperatively manage congestion. We also discuss the effect of sector allocations on profits between SPs, some limitations of the proposed approach, and promising future directions in the development of traffic management strategies for advanced air mobility systems.

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Appendix

A. Marginal Contribution Example

In Table A1, we lay out the marginal contribution of every SP in every possible ordering for the example flight illustrated in Fig. 1. Summing each column and dividing by the number of orderings gives the Shapley value profit φ_j^f for SP j.

Table A1 Marginal contributions for each coalition formation permutation

	Marginal contribution			
Ordering	SP 1	SP 2	SP 3	SP 4
(1,2,3,4)	0	0	0	$3\sqrt{2}$
(1,2,4,3)	0	0	0	$3\sqrt{2}$
(1,3,2,4)	0	0	0	$3\sqrt{2}$
(1,3,4,2)	0	$4-2\sqrt{2}$	0	$5\sqrt{2}-4$
(1,4,2,3)	0	$3\sqrt{2}$	0	0
(1,4,3,2)	0	$4-2\sqrt{2}$	$5\sqrt{2}-4$	0
(2,1,3,4)	0	0	0	$3\sqrt{2}$
(2,1,4,3)	0	0	0	$3\sqrt{2}$
(2,3,1,4)	0	0	0	$3\sqrt{2}$
(2,3,4,1)	$3\sqrt{2}$	0	0	0
(2,4,1,3)	$3\sqrt{2}$	0	0	0
(2,4,3,1)	$3\sqrt{2}$	0	0	0
(3,1,2,4)	0	0	0	$3\sqrt{2}$
(3,1,4,2)	0	$4-2\sqrt{2}$	0	$5\sqrt{2}-4$
(3,2,1,4)	0	0	0	$3\sqrt{2}$
(3,2,4,1)	$3\sqrt{2}$	0	0	0
(3,4,1,2)	$5\sqrt{2}-4$	$4-2\sqrt{2}$	0	0
(3,4,2,1)	$3\sqrt{2}$	0	0	0
(4,1,2,3)	0	$3\sqrt{2}$	0	0
(4,1,3,2)	0	$4-2\sqrt{2}$	$5\sqrt{2}-4$	0
(4,2,1,3)	$3\sqrt{2}$	0	0	0
(4,2,3,1)	$3\sqrt{2}$	0	0	0
(4,3,1,2)	$5\sqrt{2}-4$	$4-2\sqrt{2}$	0	0
(4,3,2,1)	$3\sqrt{2}$	0	0	0
ϕ_j	1.670	0.646	0.256	1.670
φ_j	0.394	0.152	0.060	0.394

B. Revenue Function Sensitivity

In Fig. B1, we demonstrate that the results shown in Sec. V.B hold across changes in the revenue function. We compare for the *Special* scenario the revenue functions $U^f = 1.5\|o - d\|_2$, $U^f = 2\|o - d\|_2$, and $U^f = 2.5\|o - d\|_2$. The Shapley mechanism continues to encourage optimal routing, while other mechanisms are inconsistent in their routing preferences.

C. Gate Sensitivity for Allocations

In this section, we show that the results presented in Sec. VI.B are independent of the structure of the gates being provided. Figure C1 replicates the results of Fig. 4 for airspace scenarios with varying numbers of gates per sector border. As the number of gates increases, the length of the optimal route decreases, and the total earnings for each SP increase. The histograms on the left side of the

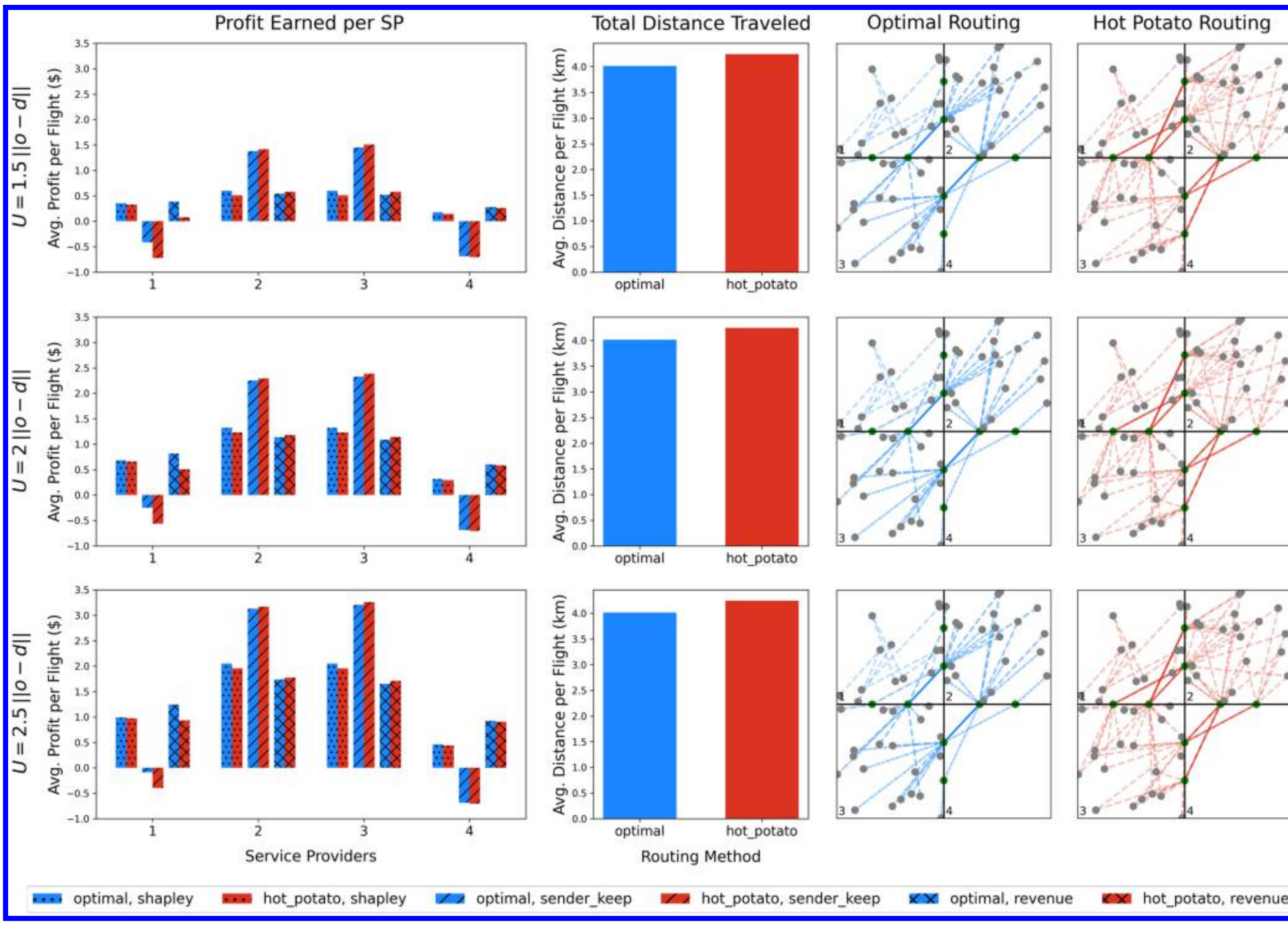

Fig. B1 Comparison of revenue functions on the *Special* scenario. Some flights may not be carried with lower revenue functions because total costs exceed revenue.

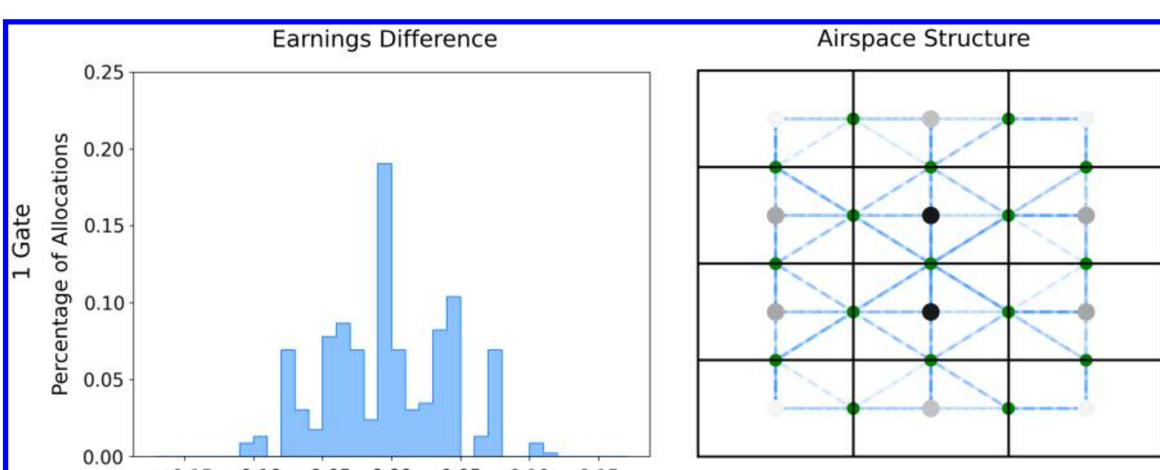

Fig. C1 Comparison of relative difference of earnings over different numbers of gates. Left: relative difference for all possible allocations. Right: optimal trajectory for each origin–destination pair.

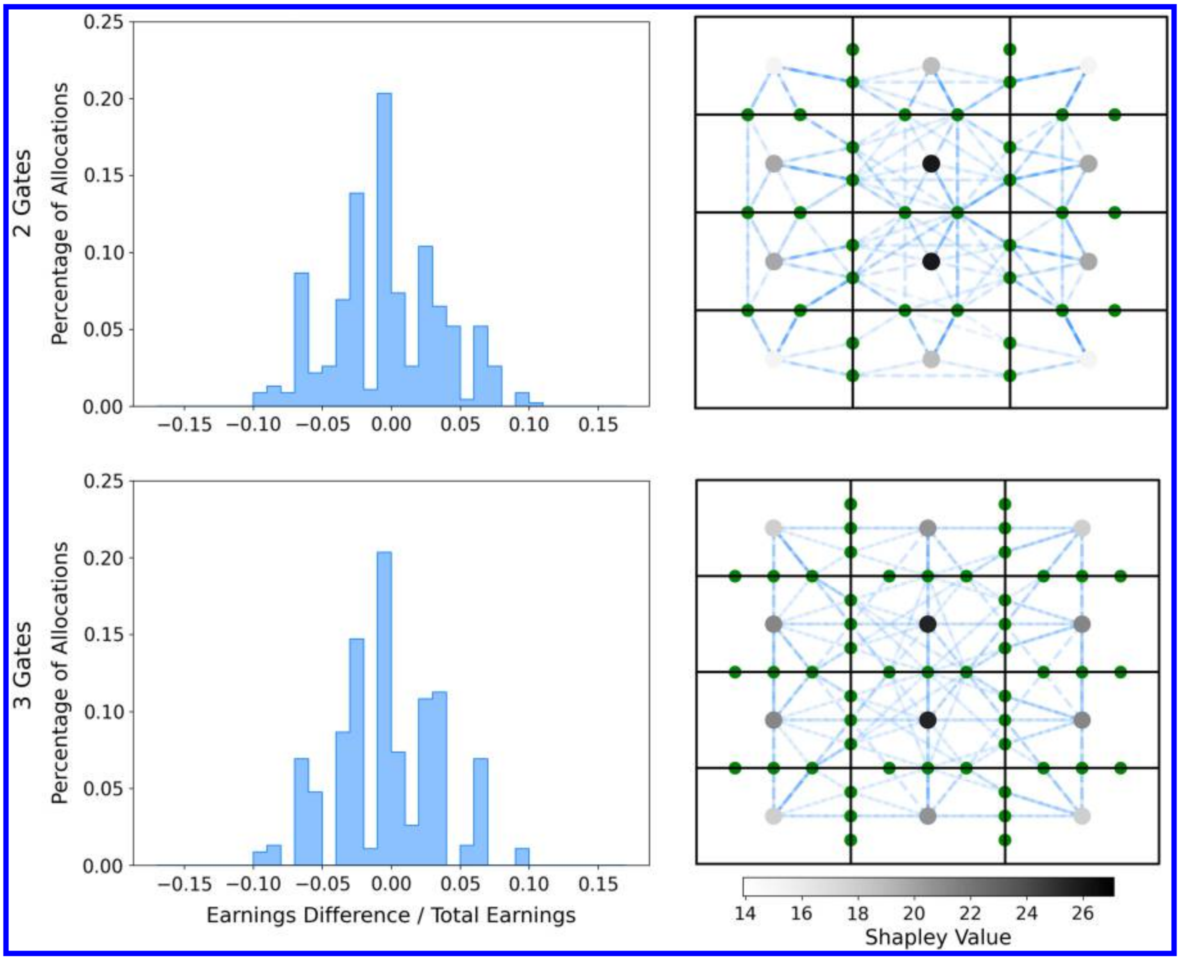

Fig. C1 (Continued).

figure show that the relative difference does not significantly change as the number of gates increases. As the number of gates provided approaches infinity, the airspace scenario becomes a fully free routing environment.

References

[1] Balakrishnan, K., Polastre, J., Mooberry, J., Golding, R., and Sachs, P., "Blueprint for the Sky: The Roadmap for the Safe Integration of Autonomous Aircraft," Airbus UTM TR, 2018, https://storage.googleapis.com/blueprint/Airbus_UTM_Blueprint.pdf.

[2] "The Future of Air Mobility: Electric Aircraft and Flying Taxis," McKinsey & Company, Nov. 2021, https://www.mckinsey.com/featured-insights/the-next-normal/air-taxis [retrieved 2 Dec. 2022].

[3] "Unmanned Aircraft Systems (UAS) Traffic Management (UTM) Implementation Plan," Federal Aviation Administration TR, Washington, D.C., July 2023, https://www.faa.gov/sites/faa.gov/files/PL_115-254_Sec376_UAS_Traffic_Management.pdf.

[4] "Urban Air Mobility (UAM) Concept of Operations Version 2.0," Federal Aviation Administration TR, Washington, D.C., April 2023, https://www.faa.gov/sites/faa.gov/files/Urban%20Air%20Mobility%20%28UAM%29%20Concept%20of%20Operations%202.0_0.pdf.

[5] "U-space ConOps (edition 3.10): U-Space Capabilities and Services to Enable Urban Air Mobility," European Organisation for the Safety of Air Navigation (EUROCONTROL) TR, 2022, https://cordis.europa.eu/programme/id/H2020_SESAR-VLD2-03-2020.

[6] "Advanced Air Mobility in Japan," Ministry of Economy, Trade and Industry (METI), Japan (METI) TR, 2021, https://www.mlit.go.jp/koku/content/Advanced_Air_Mobility_in_JAPAN_2021.pdf.

[7] McLeod, D., and Heimbigner, D., "A Federated Architecture for Database Systems," *AFIPS '80: Proceedings of the May 19-22, 1980, National Computer Conference*, Assoc. for Computing Machinery, New York, 1980, pp. 283–289.
https://doi.org/10.1145/1500518.1500561

[8] Hammer, M., and McLeod, D., "On Database Management System Architecture," Massachusetts Inst. of Technology TR MIT-LCS-TM-141, 1979.

[9] Serrano, M., Davy, S., Johnsson, M., Donnelly, W., and Galis, A., "Review and Designs of Federated Management in Future Internet Architectures," *The Future Internet*, Springer, Berlin, 2011, pp. 51–66.

[10] Deloitte Consulting, L. L. P., "UAM Vision Concept of Operations (ConOps) UAM Maturity Level (UML) 4—v1.0," NASA TR 20205011091, Dec. 2020.

[11] Ma, R. T. B., Chiu, D.-M., Lui, J. C. S., Misra, V., and Rubenstein, D., "On Cooperative Settlement Between Content, Transit and Eyeball Internet Service Providers," *ACM CoNEXT 2008*, IEEE Publ., Piscataway, NJ, 2008.
https://doi.org/10.1145/1544012

[12] Ma, R. T. B., Chiu, D.-M., Lui, J. C. S., Misra, V., and Rubenstein, D., "Internet Economics: The Use of Shapley Value for ISP Settlement," *IEEE/ACM Transactions on Networking*, Vol. 18, No. 3, 2010, pp. 775–787.
https://doi.org/10.1109/TNET.2010.2049205

[13] Shapley, L. S., "Notes on the n-Person Game—II: The Value of an n-Person Game," RAND Corp. TR RM 670, 1951.

[14] User:Ludovic.ferre, "File: Internet Connectivity Distribution & Core.svg—Wikipedia," 2010, https://commons.wikimedia.org/wiki/File:Internet_Connectivity_Distribution_%26_Core.svg.

[15] McKnight, L. W., and Bailey, J. P., *Internet Economics*, MIT Press, Cambridge, MA, 1997.
https://doi.org/10.7551/mitpress/3867.001.0001

[16] Cohen-Almagor, R., "Internet History," *International Journal of Technoethics*, Vol. 2, No. 2, 2011, pp. 45–64, https://services.igi-global.com/resolvedoi/resolve.aspx?doi=10.4018/jte.2011040104.
https://doi.org/10.4018/jte.2011040104

[17] Jahnke, A., "Level 3, Cogent Spat Affects 15 Percent of Internet," 2005, http://www.cio.com/article/252501/internet-level-3-cogent-spat-affects-15-percent-of-internet.html.

[18] Faratin, P., Clark, D., Gilmore, P., Bauer, S., Berger, A., and Lehr, W., "Complexity of Internet Interconnections: Technology, Incentives and Implications for Policy," *35th Research Conference on Communication, Information and Internet Policy (TPRC)*, TPRC, Schertz, TX, 2007.

[19] Ball, M. O., Donohue, G. L., and Hoffman, K., "Auctions for the Safe, Efficient, and Equitable Allocation of Airspace System Resources," *Combinatorial Auctions*, edited by P. Cramton, Y. Shoham, and R. Steinberg, MIT Press, Cambridge, MA, 2005, pp. 507–538, http://mitpress.universitypressscholarship.com/view/10.7551/mitpress/9780262033428.001.0001/upso-9780262033428-chapter-21. https://doi.org/10.7551/mitpress/9780262033428.003.0021

[20] Vossen, T. W. M., and Ball, M. O., "Slot Trading Opportunities in Collaborative Ground Delay Programs," *Transportation Science*, Vol. 40, No. 1, 2006, pp. 29–43. https://doi.org/10.1287/trsc.1050.0121

[21] Brugnara, I., Castelli, L., and Pesenti, R., "A Market Mechanism for Multiple Air Traffic Resources," *Transportation Research Part E: Logistics and Transportation Review*, Vol. 178, Oct. 2023, Paper 103255. https://doi.org/10.1016/j.tre.2023.103255

[22] Chin, C., Qin, V., Gopalakrishnan, K., and Balakrishnan, H., "Traffic Management Protocols for Advanced Air Mobility," *Frontiers in Aerospace Engineering*, Vol. 2, May 2023, Paper 1176969. https://doi.org/10.3389/fpace.2023.1176969

[23] Qin, V., and Balakrishnan, H., "Cost-Aware Congestion Management Protocols for Advanced Air Mobility," *10th International Conference on Research in Air Transportation*, Organizers Marc Bourgois (Eurocontrol), Eric Niederman (FAA), 2022, Paper 45, https://dspace.mit.edu/bitstream/handle/1721.1/145406/ICRAT2022_paper_45.pdf?sequence=1&isAllowed=y.

[24] Clare, G., Richards, A., Escartin, J., Martinez, D., Cegarra, J., and Alvarez, L. J., "Air Traffic Flow Management Under Uncertainty: Interactions Between Network Manager and Airline Operations Centre," Organizers Peter Hothman (SESAR JU), Colin Meckiff (EUROCONTROL), 2012, Paper 13, https://sesarju.eu/sites/default/files/SID_2012-13.pdf.

[25] Ivanov, N., Jovanovic, R., Fichert, F., Strauss, A., Starita, S., Babic, O., and Pavlovic, G., "Coordinated Capacity and Demand Management in a Redesigned Air Traffic Management Value-Chain," *Journal of Air Transport Management*, Vol. 75, March 2019, pp. 139–152. https://doi.org/10.1016/j.jairtraman.2018.12.007

[26] Ma, R. T., Chiu, D.-M., Lui, J. C. S., Misra, V., and Rubenstein, D., "Interconnecting Eyeballs to Content: A Shapley Value Perspective on ISP Peering and Settlement," *Proceedings of the 3rd International Workshop on Economics of Networked Systems*, Assoc. for Computing Machinery, New York, 2008, pp. 61–66. https://doi.org/10.1145/1403027.1403041

[27] Dai, B., and Chen, H., "Profit Allocation Mechanisms for Carrier Collaboration in Pickup and Delivery Service," *Computers & Industrial Engineering*, Vol. 62, No. 2, 2012, pp. 633–643. https://doi.org/10.1016/j.cie.2011.11.029

[28] Deng, Y., Shao, S., Mittal, A., Twumasi-Boakye, R., Fishelson, J., Gupta, A., and Shroff, N. B., "Incentive Design and Profit Sharing in Multi-Modal Transportation Network," 2022, http://arxiv.org/abs/2101.03297.

[29] Myerson, R. B., "Conference Structures and Fair Allocation Rules," *International Journal of Game Theory*, Vol. 9, No. 3, 1980, pp. 169–182. https://doi.org/10.1007/BF01781371

[30] Ma, R. T., Lui, J. C., Chiu, D.-M., Misra, V., and Rubenstein, D., "The Shapley Value: Its Use and Implications on Internet Economics," *46th Annual Allerton Conference on Communication, Control, and Computing*, Inst. of Electrical and Electronics Engineers, New York, 2008, pp. 1094–1096. https://doi.org/10.1109/ALLERTON.2008.4797681

[31] Shoham, Y., and Leyton-Brown, K., *Multiagent Systems: Algorithmic, Game-Theoretic, and Logical Foundations*, Cambridge Univ. Press, Cambridge, England, U.K., 2008, Chap. 12. https://doi.org/10.1017/CBO9780511811654

[32] Skibski, O., Rahwan, T., Michalak, T. P., and Wooldridge, M., "Enumerating Connected Subgraphs and Computing the Myerson and Shapley Values in Graph-Restricted Games," *ACM Transactions on Intelligent Systems and Technology*, Vol. 10, No. 2, 2019, pp. 1–25. https://doi.org/10.1145/3235026

[33] "About Auctions," Federal Communications Commission, 2023, https://www.fcc.gov/about-auctions [retrieved Nov. 2023].

[34] "86 FR 4390: Remote Identification of Unmanned Aircraft," Federal Aviation Administration, 2021 [retrieved Oct. 2021].

[35] Chin, C., Gopalakrishnan, K., Egorov, M., Evans, A., and Balakrishnan, H., "Efficiency and Fairness in Unmanned Air Traffic Flow Management," *IEEE Transactions on Intelligent Transportation Systems*, Vol. 20, No. 9, 2021, pp. 5939–5951. https://doi.org/10.1109/TITS.2020.3048356

[36] Chin, C., Gopalakrishnan, K., Balakrishnan, H., Egorov, M., and Evans, A., "Protocol-Based Congestion Management for Advanced Air Mobility," *Journal of Air Transportation*, Vol. 31, No. 1, 2023, pp. 35–44. https://doi.org/10.2514/1.D0298

[37] Delgado, L., "European Route Choice Determinants: Examining Fuel and Route Charge Trade-Offs," *Proceedings of the 11th USA/Europe Air Traffic Management Research and Development Seminar, ATM 2015*, Organizers Eric Niederman (FAA), Colin Meckiff (EUROCONTROL), 2015, Paper 487, http://www.scopus.com/inward/record.url?eid=2-s2.0-84944548423&partnerID=MN8TOARS.