Practical Algorithms for Next Generation Air Transportation Systems

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The air transportation system, which began in the 1920s as a means of transporting passengers and mail between a handful of airports within the United States, has evolved into a large, complex system which interacts with global and regional economies, and which transports 2.1 billion passengers and 39 million tons of freight per year. The steady increase in both passenger and cargo flights has led to an increase in flight delays, both in terms of the number of flights incurring delays, and the total amounts of delay incurred.The Joint Economic Committee of the US Senate estimates that commercial aviation delays cost U.S. airlines more than $19 billion per year in direct operating costs alone. With air transportation having become the backbone of global commerce, the indirect costs to passengers and businesses are much higher, and are estimated to be about $41 billion annually.

The demand for air traffic in the United States is expected to increase to between 2 and 3 times current values by the year 2025. Similar growth in demand is expected in Europe, while emerging markets such as China, the Middle East and India are expected to see even larger increases in air traffic operations. As a result, congestion delays will increase unless new air traffic management solutions are developed and implemented. This realization has motivated research efforts in both the United States (NextGen), and Europe (SESAR).

These observations motivate the development of practical algorithms for next generation air transportation systems: techniques that will help achieve an efficient, robust, and safe air transportation system, while simultaneously overcoming the challenges imposed by uncertainty, competing interests, and environmental considerations. This paper proposes that, by analyzing the large amounts of weather, flight, and airline cost data available, we can (1) develop optimization algorithms that use weather forecasts to determine schedules that are robust to uncertainty, (2) design market-based mechanisms that manage the competitive behavior of airlines and achieve an efficient allocation of resources, and (3) incorporate environmental impact costs and constraints into our optimization formulations to achieve sustainable and green air traffic operations.

Managing operations in an air transportation system involves solving many complex resource allocation problems. In the course of a flight from an origin airport to a destination, an aircraft trajectory passes through several regions of the airspace, using both airport (gates, taxiways, runways) and airspace resources. Physical constraints and safety considerations limit the capacity of almost all airspace and airport surface resources. Air traffic control is currently performed by human controllers; as a result, the capacity of the airspace is further constrained by their workload and their ability to safely maintain separation between aircraft. While runway operations are typically considered the limiting factors on airport arrival and departure rates, there has been an increase in incidents of surface gridlock, caused by the limited availability of taxiways or gates.

Control and resource allocation decisions are made at two levels: the strategic or "outer-loop" control (hours to a day ahead of operations), and the tactical or "inner-loop" control (minutes to an hour ahead). Planning at the strategic level requires the allocation of appropriate resources among the aircraft in order to determine the scheduled trajectories of the flights. The ability to fly the pre-planned trajectories depends on the weather that the aircraft need to operate in. As actual conditions materialize, air traffic controllers tactically control operations by regulating handoffs into and out of their facilities, to ensure that capacity constraints are satisfied at all times. Techniques from optimization and control are well suited to tackle the the wide variety of coordination and resource allocation problems across multiple time-scales that need to be solved in air transportation. However, the practical application of these methods to air traffic management has remained so far unsuccessful due to the neglect of challenges posed by real-world environments, such as system uncertainty, competing stakeholders, and environmental-impact concerns.

Goals and challenges

The overall objective in developing algorithms for air traffic management is to achieve an efficient, robust and safe air transportation system. In this section, these goals, and the real-world challenges that need to be overcome in order to achieve these objectives in practice, are described.

1. **Efficiency.** Achieving an efficient allocation of resources is necessary for the overall functioning of the system. The most common metric used to measure efficiency is *delay*, defined as the difference between the time at which an operation (departure, arrival, crossing a way-point in the airspace) occurred and the time at which it was scheduled to occur. However, depending on the type of operation being considered, there could be other metrics that measure the efficiency of operations, such as the per-passenger delay. For arrival and departure runway operations, *throughput* is an important metric, since it determines the capacity of the airport, and the rate at which arrivals and departures can be scheduled to the airport. Given such a diverse range of metrics, it is also necessary to evaluate and understand the tradeoffs between them.
2. **Robustness.** The performance of air transportation system is determined by many extraneous factors such as the weather, aircraft trajectories, demand for service, etc., and is therefore subject to much uncertainty. For the smooth functioning of the system, we require that it be robust – *i.e.*, perturbations in one part of the system should not result in long delays, or require a large amount of rescheduling of flights. While robustness could be achieved by being overly conservative in the scheduling and by operating at the worst-case estimates of capacity, that would greatly degrade efficiency.
3. **Safety.** Safety is of paramount importance in any air transportation system. A major aspect of air traffic safety is maintaining separation between aircraft and preventing collisions, as are mandated by the Federal Aviation System (FAA) and similar organizations. Algorithms developed for air traffic management will have to be evaluated and shown to satisfy the safety requirements before being implemented.

These objectives are difficult to achieve in practice because of the challenges posed by the real system. The three key challenge problems that need to be solved by any practical solution are:

1. **Uncertainty.** The actual capacity of the system depends on the levels of convective weather, turbulence, icing, ceiling and visibility, and surface winds at the airports and in the airspace. In addition to the capacity uncertainty due to uncertain weather forecasts, there is also uncertainty in the demand due to unscheduled emergency flights, uncertain travel times, and international flights. The presence of uncertainty challenges the objective of achieving efficient and robust operations. There are two promising directions of research that we pursue in order to best accommodate uncertainty and increase the robustness of air traffic operations: the first is the *investigation and validation of weather forecast products* in order to determine how best to integrate weather forecasts into the decision-making; the second is the development of *robust scheduling algorithms for air traffic management*. The objective

of the former effort is to determine to level of capacity uncertainty associated with weather forecasts (for example, how robust are viable routes predicted by the forecasts, and the likelihood of route blockages due to a change in weather conditions), while the latter effort will develop algorithms that will utilize the results of the former in order to determine the most efficient and robust decisions.

2. **Multiple stakeholders with competing interests.** Aircraft are operated by airlines, which are inherently independent, self-interested agents. Efficient operations require that airlines share information on flight status, mechanical delays and preferred routes with air traffic control, and do so truthfully. By incorporating concepts from game theory and mechanism design, it is possible to develop *algorithms for the scheduling (and rescheduling) of air transportation resources that address issues of equity and incentives for gaming* among airlines.
3. **Environmental concerns.** Environmental considerations such as emissions and noise are increasingly imposing constraints on air traffic operations, both in the skies and at airports. The identification of the environmental constraints, and the planning of operations that are efficient and yet green will be essential to any practical and socially acceptable plan for future air transportation systems. In addition to lowering aircraft emissions, a reduction of fuel burn will increase the sustainability of the air transportation system. These concerns need to be addressed through the development of *techniques for improving the environmental performance of air transportation systems*, both on the ground and in the air. It is also important to study the inherent tradeoffs associated with the objectives of system throughput and environmental performance.

To summarize, there is a clear need for a new set of optimization algorithms and market-based mechanisms that will be able to handle the steadily increasing air traffic load. Understanding weather phenomena and their effect on aircraft operations will provide insight into better strategic and tactical control of air traffic. Equitable resource allocation algorithms for air transportation systems will encourage truthful reporting of operating costs and preferences by the airlines, provide incentives for information sharing, and ultimately improve passenger experience. Green air traffic management algorithms will support increased air traffic loads with a tolerable impact on the environment. The solutions developed will offer a more efficient, robust and safe air transportation system by accommodating regulatory constraints, and shape air transportation policy. The lessons learned from this effort will potentially provide insights into the development of algorithms for other large-scale infrastructure systems, such as rail and road transportation systems, telecommunication networks, and power systems.

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