Transportation Network Topologies

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Abstract

A discomforting reality has materialized on the transportation scene: our existing air and ground infrastructures will not scale to meet our nation's 21st century demands and expectations for mobility, commerce, safety, and security. The consequence of inaction is diminished quality of life and economic opportunity in the 21st century. Clearly, new thinking is required for transportation that can scale to meet to the realities of a networked, knowledge-based economy in which the value of time is a new coin of the realm. This paper proposes a framework, or topology, for thinking about the problem of scalability of the system of networks that comprise the aviation system. This framework highlights the role of integrated communication-navigation-surveillance systems in enabling scalability of future air transportation networks. Scalability, in this vein, is a goal of the recently formed Joint Planning and Development Office for the Next Generation Air Transportation System.

New foundations for 21st thinking about air transportation are underpinned by several technological developments in the traditional aircraft disciplines as well as in communication, navigation, surveillance and information systems. Complexity science and modern network theory give rise to one of the technological developments of importance. Scale-free (*i.e.,* scalable) networks represent a promising concept space for modeling airspace system architectures, and for assessing network performance in terms of scalability, efficiency, robustness, resilience, and other metrics. The paper offers an air transportation system topology as framework for transportation system innovation. Successful outcomes of innovation in air transportation could lay the foundations for new paradigms for aircraft and their operating capabilities, air transportation system architectures, and airspace architectures and procedural concepts. The topology proposed considers air transportation as a system of networks, within which strategies for scalability of the topology may be enabled by technologies and policies. In particular, the effects of scalable ICNS concepts are evaluated within this proposed topology.

Alternative business models are appearing on the scene as the old centralized hub-and-spoke model reaches the limits of its scalability. These models include growth of point-to-point scheduled air transportation service (*e.g.,* the RJ phenomenon and the "Southwest Effect"). Another is a new business model for on-demand, widely distributed, air mobility in jet taxi services. The new businesses forming around this vision are targeting personal air mobility to virtually any of the thousands of origins and destinations throughout suburban, rural, and remote communities and regions. Such advancement in air mobility has many implications for requirements for airports, airspace, and consumers. These new paradigms could support scalable alternatives for the expansion of future air mobility to more consumers in more places.

Introduction

A discomforting reality has materialized on the transportation scene: our existing air and ground infrastructures will not scale to meet our nation's 21st century demands and expectations for mobility, commerce, safety, and security. The consequence of inaction is diminished quality of life and economic opportunity in the 21st century. Clearly, new thinking is required for transportation that can scale to meet to the realities of a networked, knowledge-based economy in which the value of time is a new coin of the realm. This paper proposes a framework, or topology, for thinking about the problem of scalability of the system of networks that comprise the aviation system. This framework highlights the role of integrated communication-navigation-surveillance systems in enabling scalability of future air transportation networks. Scalability, in this vein, is a goal of the recently formed Joint Planning and Development Office for the Next Generation Air Transportation System. In his book Free Flight[1], James Fallows argues that air transportation is unique in being one of the last industrial segments in western society to modernize. In making this point, he contrasts the ability of the current aviation system to satisfy consumers' expectations with the revolutions that have taken place in many other industrial arenas where products and services have become highly customized and personalized to individual expectations. From a consumers' perspective, the aviation system largely offers a "one size fits all," "take it or leave it" experience. From a provider's perspective, we have evolved to practicing "demand management" as a means of doling out that which we see today as a scarcity: airspace capacity. Why has aviation been so slow to change? What forces inhibit change? What would transformation of the aviation system look like, both from a consumer and from a provider perspective?

It has been projected[2] that the current NAS will not be able to meet passenger volume much less the quality of service demands expected by future consumers. A primary expectation, total time-to-travel, is becoming an important issue as the business segment of the public has woven flying into their everyday lives. A counterintuitive fact illuminates the challenge in reducing time-to-travel. For hub-and-spoke trips of about 500 nautical miles, the doorstep-to-destination speeds average around 75 knots, with the distribution ranging between about 15 knots and about 95 knots. This average prevails in spite of the fact that the aircraft themselves fly at speeds faster than 400 knots[3].

Customers have adopted the mantra of "mass customization" for a price (CIO Magazine Feb. 15, 1998) and are ready and willing to pay for quality-of-service (QoS) depending upon their needs at the time. For a price, travelers may find it acceptable to give up a little comfort for savings or conversely put a premium on the freedom of being able to travel directly to and from where and when they would like to. One only has to examine the model of fractional ownership of small jets to see an example of where the future of air travel is heading.

While it is fairly easy to point out the forces constraining the scalability of the current system (regulation, economics, infrastructure, *e.g.*), until recently, there has been little written about what forces could be put into place that would facilitate the ability of the system to scale to meet future needs. The vision for transformation of the aviation system, as proposed by the Joint Planning and Development Office for the Next Generation Air Transportation System[4, 5] provides a framework for approaching these questions.

Unlike other relatively less complex national systems (manufacturing, food, banking, etc.) that are somewhat insulated by changes in demand or supply due to network topologies, the NAS is a more complex mix of consumers, producers and suppliers, any one of which can disrupt travel service for all at a moments notice. This 'brittleness'[*] of the system is the Achilles heal to the industry and the National Economy as has been witnessed by recent events including 9/11 and security incidents at airports (e.g. November 2001 Atlanta airport, July 2002 Los Angeles airport), one incident can cause major disruption

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[*] A system is defined as 'brittle' if small changes in its operating conditions, inputs, or other factor causes the system to fail completely rather than experience a graceful degradation.

or a halting of service. Weather related incidents also cause much damage to the perception of service reliability (and reputation) to the national air-transportation system.

The aviation community faces the daunting challenge of creating strategies for policies, technologies, infrastructure, and business models that pave a path to the future. The challenge lies in creating strategies that lead to scalable solutions for meeting growth in demand, including strategies affecting the communication, navigation and surveillance (CNS) system infrastructure. The 20th century transition from analog to digital appears to be merely a prelude for the emergence of 21st century networking of aircraft, airspace services, airports, and consumers of air transportation services. At the heart of this emergence, advancing to the drumbeat of Moore's Law and riding the wave of the revolution in digital bandwidth, integrated, networked CNS technologies stand to play a core role in enabling transformation of the U.S. aviation system. The power of future networked systems architectures to transform aviation will enable future scalable airspace architectures, future aircraft architectures, as well as new approaches to safety and security in the system of systems we know as aviation.

The transformational path forward will be enabled in part by more scalable business models based on technology deployed within an improved regulatory framework, in organizations that function effectively outside traditional stove-piped boundaries.

Transformation

Transformation of the aviation system implies a future that will not consist of a slightly refined and improved version of the past, if for no other reason than the architecture of the current system (including airports, airspace, airline hub-and-spoke, and past air taxi business models and their technologies) does not appear scalable to meet the future. For purposes of this dialogue, the term "scalable" when applied to transportation networks, refers to the agility of business models, CNS infrastructure, and airspace architecture to accommodate change, both in demand-side and supply-side dynamics of complex and adaptive transportation system networks. Further description of the nature of scalability will be provided below, in the context of network theory and small world network behaviors.

The elements of the current system architecture or topology do not exhibit scalability. At the highest level of the architecture, the historical business models doe not possess the ability to reach beyond the current hub-and-spoke infrastructure of about 500 airports to deliver transportation services to certain markets. The continuing loss of air service for a growing number of communities not served by the hub-and-spoke system is one example. To wit, smaller communities continue to lose service or frequency of service over time[6]. Within the National Airspace System, the ability to expand the utility of airspace is not readily scalable. Historically, the scalability of airspace utility is inhibited by time-consuming and expensive deployment of terrestrial CNS infrastructure, in the form of navigation aids and surveillance systems (as contrasted with airborne-based systems) for example. Within the technology base of the existing airspace system, the reliance on analog (as contrasted with digital) systems for communication, navigation, and surveillance represents an inhibitor to scalability. Even the scalability of air service business models is inhibited by the economics of available aircraft and the airport and airspace infrastructure, among other factors (labor costs for example).

The current NAS appears to be reaching its limits of growth due to a number of reasons. Government policies and regulations have created an environment that was well suited for the propeller and jet phases of commercial operations in the relatively centralized hub-and-spoke architecture. In these phases technology (communications) and organizational processes (Frederick Taylor and design of organizations) lead to businesses that were hierarchical in nature and tended to out perform other architectures. These government policies coupled with technology and processes fostered development of the types of centralized hub-and-spoke NAS network structures we see today. The current hub-and-spoke NAS architecture is not sustainable[7]. Recent studies indicate that it takes a minimum of fifteen years to build a new runway at hubs[8]. These characteristics do not constitute an architecture that is able to meet market demand in a timely fashion.

A transformed, scalable transportation system would expand air mobility to reach more markets, not contract to reduce air mobility as our system does today. There are valid historical antecedents behind the development of the extant system, including the decades-long march of technological progress leading to radar, VHF navigation and communication and the like. However, in the interests of articulating the vision for transformation of the aviation system, this paper focuses on the potential for scalability of our aviation system of networks, and in particular the import of intelligent CNS (iCNS) concepts to support scalability.

It will be important to acknowledge the long-term effects of transportation systems on population related migration and the development of land use patterns and national policy considerations.

Envisioning a Transformed NAS

Because the kinds of challenges we face in transforming the aviation system involve complexity and adaptivenss, network theory and network-derived topologies can guide thinking about strategies for NAS transformation, transformational business models, and strategies for underlying technologies, including iCNS strategies. The ability to predict the system-level (or network) behavioral responses of proposed changes is extremely important. For example:

- What are the effects and consequences as air transportation evolves beyond a centralized hub-and-spoke to an increasingly decentralized point-to-point model?
- How might consumer travel behavior change if large numbers of jet taxis in fleet operations appear in the market?
- What effects on air traffic service requirements and airspace capacity result as Unmanned Air Vehicles (UAVs) enter the NAS?
- Which policy interventions lead to reduced total time-of-travel time for individuals?
- What aircraft design requirements would derive from different air transportation network topologies?

The biggest challenge posed these questions is that the answers result from collective phenomena of networks. These collective phenomena result from the behavior AND interactions of tens, hundreds or thousands of participants who may have a broad range of behavioral responses to the situation they are encountering; behavioral moderators include self-interest, profit motive, state of mind, social context, economic factors, political situation, etc. The aggregate result is therefore difficult to predict using traditional linear, top-down or state analytical approaches: the phenomenon emerges from the behaviors and interactions of the numerous units that compose the air transportation system.

Proposed ideas for changing the NAS should not be contemplated lightly, due to the sheer size and complexity of the system. Instead it will require a fundamental reconsideration of how such complex systems are analyzed and designed if the system to evolve remains productive and viable. Traditional methods for analyzing changes to complex systems fail when applied to highly dynamic and interconnected systems such as the Internet or the NAS. Recent developments in the study of complex adaptive systems (CAS) and network theory, in particular, have led a number of researchers at NASA Langley to begin preliminary investigations into the applicability of the latest developments in complex system theory to the analysis and design of alternative transportation architectures[9].

Network analysis is a way of describing and understanding system structures, but does not deal with the activity that creates structure, that is, how the network is used. Agent-based modeling is a natural method of creating models with behavior and dynamics that can allow for network analysis. Utilizing network analysis as a design tool can provide a powerful method for creating air transportation networks with specific system behaviors.

Once an agent-based model has been constructed, network analysis techniques can be used to predict the behaviors of the system or help to design specific properties into the system. Network analysis can help to answer specific air transportation questions such as:

- What mitigations are possible when an airport (a node) is closed due to the weather?
- How quickly does a failure in one part of a network of systems propagate and impact the operations of other parts of the network?
- What new air-routes could be opened up to save passenger travel time?
- What mitigations can be designed into networks to increase surge capacity?
- What is the effect of varying selections of locations of hubs?

Analysis of networked systems reveals important properties that need to be considered when designing air transportation networks.

In agent-based modeling (ABM), systems are modeled as collections of autonomous decision-making entities, called agents. Each agent individually assesses its situation and makes decisions based upon a set of rules. Agents may execute various behaviors appropriate for the system they represent – for example, transporting, producing, consuming, or selling. Repetitive, competitive interactions between agents are a feature of agent-based modeling, which relies on the power of computers to explore dynamics out of the reach of pure mathematical methods[10]. At the simplest level, an agent-based model consists of a system of agents and the relationships between them. Even a simple agent-based model can exhibit complex behavior patterns[11] and provide valuable information about the dynamics of the real-world system that it emulates. In addition, agents may be capable of evolving, allowing unanticipated behaviors to emerge.[12] Sophisticated ABM sometimes incorporates neural networks and genetic algorithms to allow realistic learning and adaptation.

The benefits of ABM over other modeling techniques can be captured in three statements: (1) ABM captures emergent phenomena, (2) ABM provides a natural description of a system, (3) ABM is flexible. ABM offers a new approach to understanding how a market works: from the ground up.

> "With their ability to replicate the step-by-step and often unpredictable process by which agents like humans interact, simulations help shed insight into emergent behavior and its attendant nonlinear events. Many people have tried to represent how a market works, for example, by writing equations that represents stocks and flows. Yet the actual workings of a market are generated through a more intricate and less predictable set of interactions between consumers and advertising, buyers and salespeople, or consumers and the overall sales environments. It is impossible to understand how the market behaves by looking at it from the top down. As properties aggregate, they change. Over the years, for example, economists have produced countless analyses on the generation of queues. They all provide a straightforward set of equation-driven models. While many provide an equation that describes how groups of people cluster into lines, none analyze how these individuals learn and adapt as they form queues." (Farrell 1998, p. 87)[13]

Most often, ABM is the most natural method for describing and simulating a system comprised of "behavioral"[14] entities. Whether one is attempting to describe a stampede, a traffic jam (Figure 2), the stock market, voters or how an organization works, agent-based modeling makes the model look closer to reality.
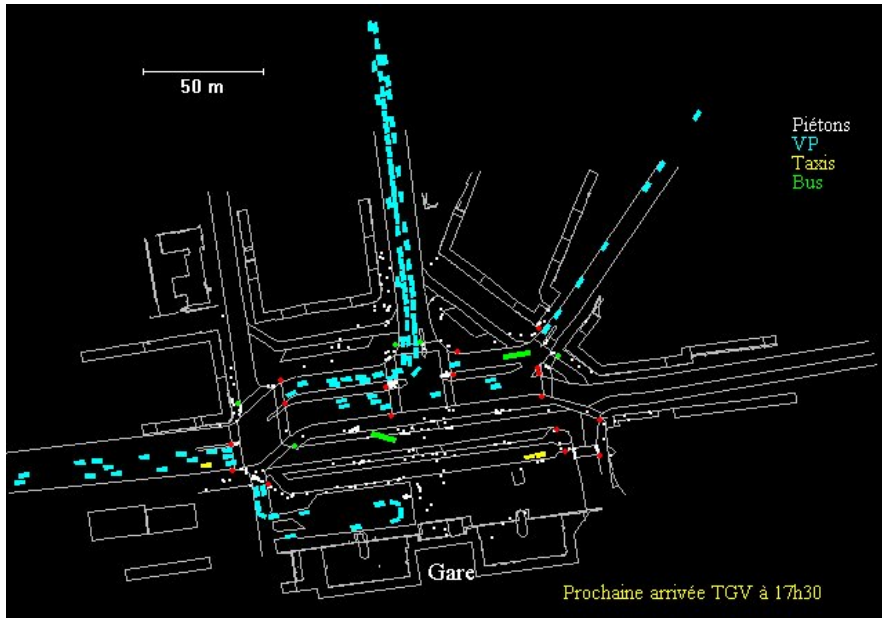
Figure 1 – Agent-based simulation of a Traffic Jam in a French City (Work by ATN)[15]

One may want to use ABM when describing the system from the perspective of its constituent units' activities is more natural, i.e., when:

- The behavior of individuals cannot be clearly defined through aggregate transition rates (equation based models).
- Individual behavior is complex. Everything can be done with equations, in principle, but the complexity of differential equations increases exponentially as the complexity of behavior increases. Describing complex individual behavior with equations becomes intractable.
- Activities are a more natural way of describing the system than processes.
- Validation and calibration of the model through expert judgment is crucial. ABM is often the most appropriate way of describing what is actually happening in the real world, and the experts can easily "connect" to the model and have a feeling of "ownership".
- Stochasticity applies to the agents' behavior. With ABM, sources of randomness are applied to the right places as opposed to a noise term added more or less arbitrarily to an aggregate equation.

One of the reasons underlying the popularity of agent-based modeling is its ease of implementation: indeed, it is easy to program an agent-based model. Because the technique is easy to use, some may be deceived into thinking that they master the concepts. But while agent based modeling is technically simple, it is also conceptually deep.

Air transportation, power, communication and social interactions all are networked systems; however some types of networks can adapt to change better than others. As portrayed in Figure 2, random networks, which resemble the U.S. highway system (simplified in left map), consist of nodes with randomly placed connections. In such systems, a plot of the distribution of node linkages will follow a bell-shaped curve (left graph), revealing a scale with most nodes having approximately the same number of links. In contrast, scale-free networks, which resemble the U.S. airline system (simplified in right map), contain hubs (red) — nodes with a very high number of links. In such networks, the distribution of node linkages follows a power law (center graph) in that most nodes have just a few connections and some have a tremendous number of links. In that sense, the system has no "scale." The defining characteristic of such networks is that the distribution of links, if plotted on a double-logarithmic scale (right graph), results in a straight line.
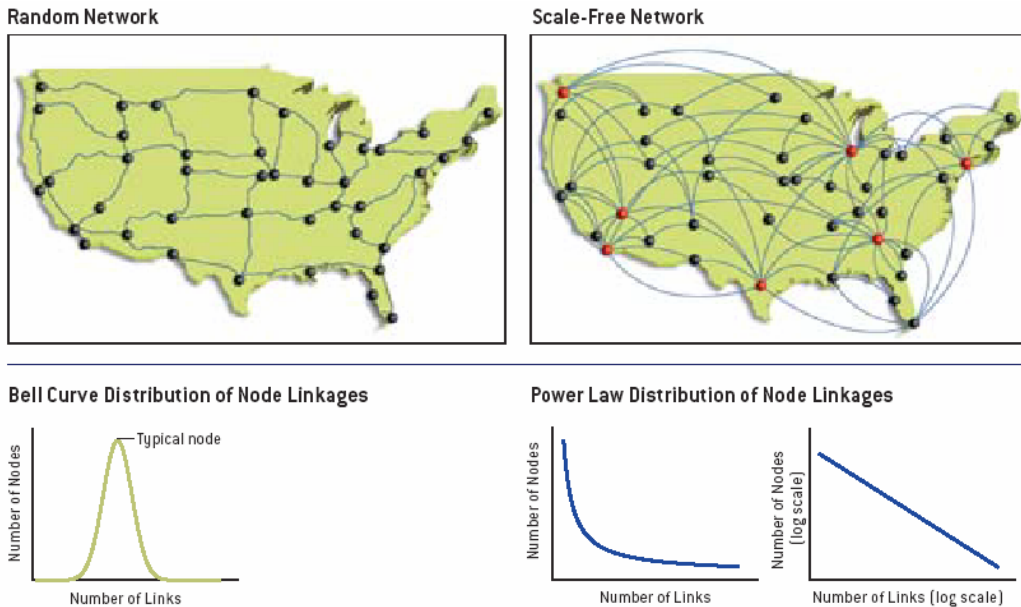
Figure 2 - Network Types (Barabasi, Bonabeau 2003)[16]

The differences between random and scale-free networks are important to aviation systems. In the case of a hub-based transportation network, not only is the network sensitive to attacks on the hubs, it is also likely that more accidents will happen at the hubs because by definition there is so much going on at the hubs. In other words, the probability that something goes wrong at a hub is much higher than at other nodes; and one single incident can bring the entire hub down (runway closure for example). It is like a targeted attack, except that it is just an accident. Hubs therefore amplify accidents in two ways: (1) they are more likely to suffer incidents/accidents because of their size and business, and (2) one incident can force authorities to shut the hub down.

The air transportation system might be designed with specific network properties in mind, such as; robustness to random failures, resilience to focused attacks or hybrids combining scale-free and random properties. For instance, scale-free networks display an amazing robustness against random failures: as there are far more small nodes than hubs, random removal will most likely hit these, but the removal of a small node does not create a significant disruption in the network topology, explaining the network's robustness against random failures. This reliance on hubs has its drawbacks as well: scale-free networks are vulnerable to focused attacks on the hubs. Random networks reveal that if a critical fraction of nodes are removed, they will break into tiny, non-communicating islands of nodes[17].

A Proposed NAS Topology

Conceptually, a case can be made that approaches to transformation must account for the behaviors present in complex and adaptive systems of networks. The development of such approaches begs for a system topology to guide transformational thinking, as well as for a lexicon to support the dialogue of transformation.

The value of a topology lies in having a framework for thinking about, modeling, analyzing, and innovating towards a transformation of the aviation system. Such a topology would need to account for the technical, economic, operational, and regulatory inter-relationships and inter-dependencies among the elements of the system. A candidate topology is offered in this paper that is intended to reflect the relationships between the networks of airports, aircraft, operators, travelers, and regulatory and business architectures that comprise the overall system of networks. The utility of such a topology would ultimately be based on its usefulness in guiding system-level strategies and in modeling behaviors
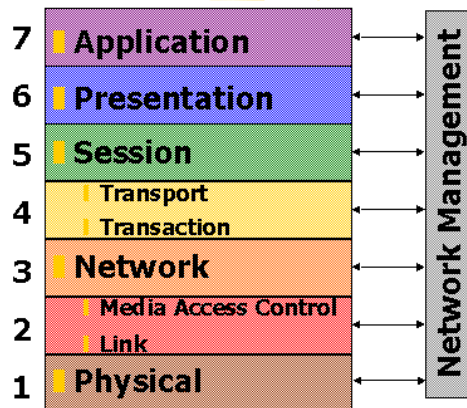
affecting demand, business innovations, policies, and technologies that lead to concepts for system transformation.

A case can also be made for the value of scalability as a signature characteristic of transformation for the future aviation system. In particular, the ability of the future system to scale to meet demand appears vital to the overall concept of transformation. Demand can be characterized as comprised of three categories: (a) known demand or that demand that is projected based on historical data and trends, (b) diverted demand or that demand that migrates from one mode, say, the hub-and-spoke system, to another, say, to highways for certain trips, and (c) induced demand, or demand that represents new consumer response to new utilities in the transportation system. As an example of one dimension of scalability is the aviation system of the future must be able to respond to these three dimensions of demand. Other examples of dimensions of scalability could be developed around the ability of the aviation system of the future to adapt to increasing aircraft operations with minimal burden in the form of infrastructure changes or workforce/workload changes. Another example would be the ability of the future system to scale with demand for use of radio frequency spectrum.

Systems of Networks

The Open System Interconnection (OSI) stack (see Figure 3) metaphor can be envisioned as layers within the transportation system with nodes and links. Consider the physical layer as the network of airports (as nodes) linked by airways and departure and approach procedures (see Figure 4), and the transport layer as the network of aircraft (as nodes) linked by ATC radar, and the operations layer as the network of pilots, crew, dispatchers and controllers (as nodes) linked by VHF communications, and the applications layer as the mobility for people, packages, and travel planners (as nodes) linked by telephone (or internet) to produce tickets or bills of lading (see Figure 5).

Figure 3 - ISO (or OSI) Stack Analogy

A. Hub-and-Spoke
Directed, Scheduled,
Aggregated

Jet Routes

User-Determined

Direct

B. Point-to-Point
Directed, Scheduled,
Aggregated

C. Distributed
Undirected, On-Demand
Dis-Aggregated

Nodes (n) = 6
Links (k) = n-1 = 5

For Example:
ORF- ORD:ORD- DEN
RIC - MSP: MSP - GFK
Tier 1,2 Carriers

Nodes (n) = 6
Links (k) = n(n-1)/2 = 15

For Example:
ORF- LAS
MDW - NWK
Tier 2,3 Carriers

Nodes (n) = 18
Links (k) = n(n-1)/2 = 153
(Three times the nodes = 10X links)
For Example:
PHF - CMH - PHF
JGG - DAN - HEF - JGG
PHF - IAD
JGG - JGG
Tier 4 Carriers, UAVs, RIAs, PAVs

Figure 4 - Physical Layer for Three Air Transportation Networks[18]

Passengers/Baggage Origins/Destinations

Trip Routings

Pilots/Crew

Duty Assignments/Routings/Rules

Aircraft

Service Routings, Airspace Procedures

Airports
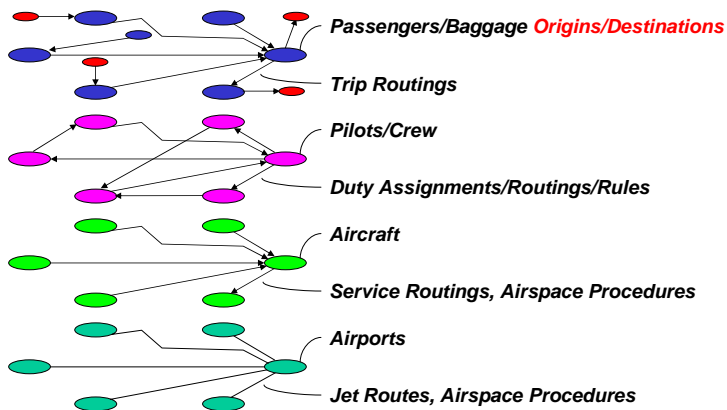
Jet Routes, Airspace Procedures

Figure 5 - Layered Topology in Air Transportation Network "Business Stack"

Figure 6 integrates these layers into a graphical representation for a candidate air transportation system topology. The picture you have now painted in your mind is a system of networks within which yet another dimension creates business stacks cutting across those other layers. That additional dimension consists of the stacks of business models that operate in this system of networks to deliver transportation services into the marketplace. Those stacks include the scheduled, aggregated business models of airlines operating under CFAR 14 Part 121 in Part 25 aircraft between Part 139 airports in one part of the system. Another business stack includes fractional, business, personal, and air taxi operators operating within a different regulatory framework in another part of the system. One lesson from thinking this way is that transformation, and therefore scalability, must account for changes to all of the layers and all of the stacks in this system of networks. Another lesson from using this framework is that this is a very complex and adaptive system, a system that requires new modeling tools to understand the interactions between these layers and stacks. These new modeling tools must be appropriate for complex and adaptive systems. Figure 7 depicts the business stacks within the topology; these business stacks are defined by the

regulatory, certification, labor, finance, and business models for each of the industry sectors in the three stacks depicted. The business stacks create the value web within which each industry sector must live, innovate, and satisfy investor and customer expectations. In many respect the confines of each business stack define the limits of a sector's ability to initiate and survive change.
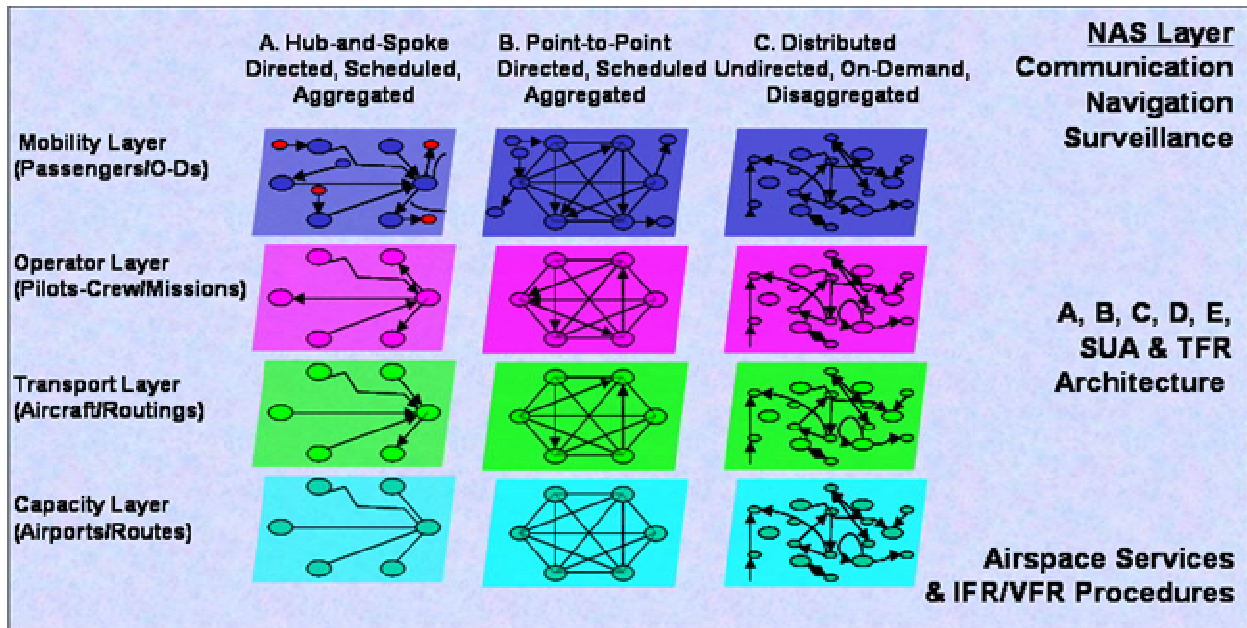

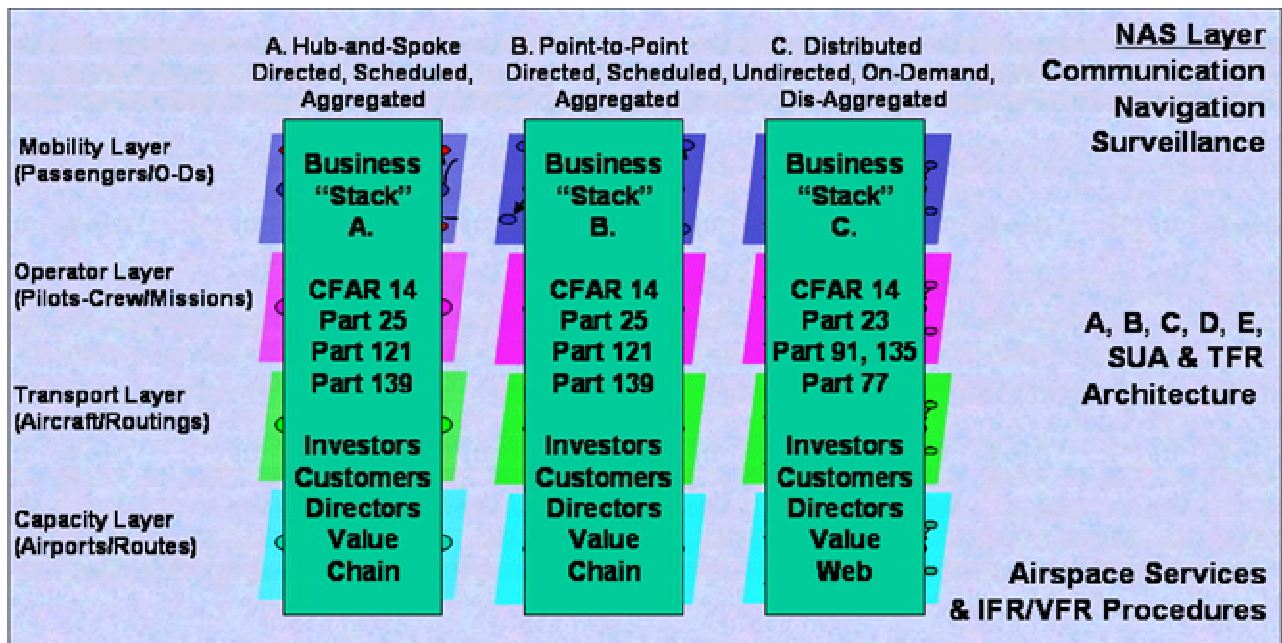**Figure 6 - Candidate Topology for Air Transportation Networks**

Figure 7 - Business Stacks in Air Transportation Topology

Focus on Technology Leading to Scalability

In the NAS there emerges lots of little niches in the market (December 11, 2003 – The Economist Magazine). Technologies play a vital role in enabling the concept of scalability for the future aviation system. Figure F relates such technologies to elements of the air transportation system topology.

- In the physical layer (with airports as nodes, linked by airways and airspace procedures) for example, scalability would be enabled through technologies and policies that enhance node fitness (airport capacity for example) as well as by enhanced link (airways) efficiencies – free flight for example.
- In the transport layer (with aircraft as nodes), scalability would be enabled by technologies and policies to lower the cost of speed to enable more markets to be reached by new generations of aircraft, and by less equipment- and labor-intensive approaches to surveillance, enabling growth of the network with minimum cost and time.
- In the operations layer (with crew, dispatchers and controllers as nodes), scalability would be enabled by such concepts as XML web-based services for networked digital communications between systems onboard aircraft and in ground-based traffic management systems (as envisioned by the Airborne Internet Consortium[19]).
- In the mobility layer (with people as nodes), scalability would be enabled by concepts that enhance the consumer-centered value criteria (on-demand transportation services between all origins and destinations for example).

The concept of global cascades in network performance is somewhat analogous to the concept of transformation of the U.S. aviation system as envisioned by the Joint Planning and Development Office for the Next Generation Air Transportation System. Global cascades are a consequence, in part, of nodal fitness, link effectiveness, and scale-free tendencies of the network. If the scalability of all layers in the air transportation system topology just described were enhanced by technologies and policies, then perhaps the potential for cascading changes throughout the topology are enhanced. If so, then it could be argued that the opportunities for innovation in the business stacks (existing and new) could be enabled.

One of the products of transformation must include the tools derived from modern developments in the science of networks, for modeling and simulating this system of networks.

Conclusion

The existing U.S. hub-and-spoke air transportation system is reaching saturation. All major, interdependent aspects of the current system, such as capacity, safety, mobility, customer satisfaction, security, communications, fuel consumption and other ecological demands, require attention if the system is to remain viable in the increasingly complex and populous world. Despite continual attempts to transform the system over the years to accommodate growing demands, it has proven remarkably resistant to change. In fact, the feasibility of accommodating the growing ambitious objectives, such as the projected two to threefold increase in demand is problematic, given the history of the attempts to improve the system.

Transformation is intended to provoke scalable technologies for communication, navigation, and surveillance infrastructure; for example, using digital in place of analog systems, and using addressable, networked communication as contrasted with low-bandwidth broadcast systems for communication. The effects will include scalable airborne capabilities for separation, sequencing, and precision guidance that enable aircraft to bring the infrastructure with them as they enter the system. In addition the effects will include new aircraft with reduced cost of speed through aeronautics technologies and through such innovations as single-crew operations that create scalability of business plans for reaching more deeply into thinner markets for air mobility.

We hear the term "system of systems" used to describe aviation and its complexities. This paper offers a framework for thinking about this complexity in more recognizable terms. The proposed topology consists of the air transportation system as a system of networks with several layers, with the network of airports as one of the layers in the system, the network of aircraft as another layer, the network of pilots,

controllers, crews, and dispatchers as a third layer, the network of people and packages traveling among origins and destinations as the top layer. In between these layers the network of airspace services, airspace structure, and communication / navigation / surveillance capabilities linking the other layers together.

This system of networks provides a way to think about scalability scales to meet demand more or less efficiently depending on how little or how much friction exists between these layers, friction in the form of cost, time, or waste of those measures. One of the goals in transformation is to enable the greatest affordable scalability in this system of networks we know as aviation.

The idea behind transformation of the technologies and the infrastructure is to enable innovation and growth in the business models for 21st century air transportation. A key to transformation lies in the strategies for scalability of the technologies, the infrastructure and the business models to be able to adapt to demand for the future. The technologies for transformation can be developed, and must be focused on the effects the technologies would have on each of the layers in the system of networks. The policy research for transformation that can be developed should be considered within the proposed model for aviation's system of networks, specifically as those policies would affect the ability of each of the business stacks in the topology to adapt and innovation to meet future demand.

[1] Fallows, J, *Free Flight*

[2] Final Report of the President's Commission on the Future of the U.S. Aerospace Industry, November, 2003 (http://www.ita.doc.gov/aerospace/aerospacecommission)

[3] Holmes, B. J.; Durham, M. H.; and Tarry, S. E.: Small Aircraft Transportation System Concept and Technologies. Journal of Aircraft, Vol. 41, No. 1, Jan-Feb 2004, pp 26-35.

[4] HR2115, Section 709-710

[5] Secretary Mineta speech, DC Aero Club, February 2004

[6] GAO: Air Service Trends at Small Communities since October 2000. GAO-02-432, March 2002.

[7] Final Report of the President's Commission on the Future of the U.S. Aerospace Industry, November, 2003 (http://www.ita.doc.gov/aerospace/aerospacecommission)

[8] Final Report of the President's Commission on the Future of the U.S. Aerospace Industry, November, 2003 (http://www.ita.doc.gov/aerospace/aerospacecommission)

[9] Transportation Network Topologies Proceedings, Published by NASA/NIA, Dec 2003

[10] Epstein J. M., Axtell R. L. (1996) *Growing artificial societies: social science from the bottom up* (MIT Press, Cambridge, MA)T; Axelrod, R. (1997) *The Complexity of Cooperation: Agent-Based Models of Competition and Collaboration* (Princeton University Press, Princeton, NJ).

[11] Epstein & Axtell, 1996

[12] Bonabeau, E. (2002b) Predicting the Unpredictable, *Harvard Business Review*, March 2002, 109-116

[13] Farrell, W. (1998) *How Hits Happen* (HarperCollins Publishers, New York)

[14] Bonabeau, E. (2002a) Agent-based modeling: methods and techniques for simulating human systems, *Proc. Nat. Acad. Sci. USA* 99, 7280-7287

[15] Client work completed by French Firm, ATN

[16] Barabasi, L., Bonabeau, E. (2003) Scale Free Networks, *Scientific American*

[17] Barabasi, L, *Linked*

[18] Holmes, B. (2003) Network Theory: A Primer and Questions for Air Transportation System Applications, NASA Unpublished Presentation

[19] Airborne Internet Consortium is developing a Collaborative Information Environment