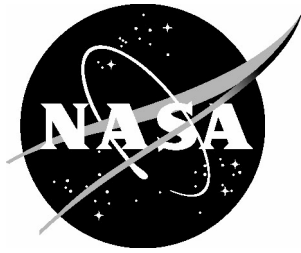


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Transportation Network Topologies

Natalia Alexandrov, Editor
Langley Research Center, Hampton, Virginia

October 2004

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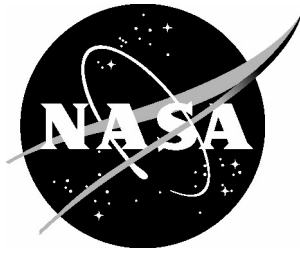
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Natalia Alexandrov, Editor
Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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PREFACE

This document contains materials from the Workshop on Transportation Network Topologies organized by the NASA Langley Research Center and the National Institute of Aerospace, held on 9-10 December 2003 in Williamsburg, Virginia.

The objective of the workshop was to bring together researchers from industry, universities, and government research laboratories in order to examine the problem of analysis and design of alternative transportation architectures in the face of changing requirements and increasing demands in air transportation. The workshop served as a forum for exchanging ideas and establishing an initial working group for the study of transportation systems.

The materials include the workshop summary, introductory comments, a recording of discussions during the workshop, a bibliography, participants' contact information, and several presentations from the workshop participants.

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PARTICIPANTS

Natalia Alexandrov, NASA Langley Research Center
Cynthia Barnhart, Massachusetts Institute of Technology
Sheila Conway, NASA Langley Research Center
Daniel DeLaurentis, Georgia Institute of Technology/National Institute of Aerospace
Joe Elliott, NASA Langley Research Center
Roger Guimerà, Northwestern University
Pamela Haley, NASA Langley Research Center
Bruce Holmes, Airspace Systems Programs Office
Rex Kincaid, College of William & Mary
Michael Kubly, Arizona State University
Phillip Lederer, University of Rochester
Kurt Neitzke, NASA Langley Research Center
John Scott, Icosystem Corporation
Marie Stella, National Defense University
Sean Tierney, Arizona State University
Antonio Trani, Virginia Polytechnic Institute and State University
Martin Waszak, NASA Langley Research Center
Leonard Wojcik, MITRE Corporation

SUMMARY

- The problem
- Modern science of complex systems
- Complex adaptive problem solving
 - Role of traditional methods
 - Role of CAS/network theory tools
- Workshop highlights
- Where do we go from here

The existing U.S. hub-and-spoke air transportation system is reaching saturation. Major aspects of the current system, such as capacity, safety, mobility, customer satisfaction, security, communications, and ecological effects, require improvements. The changing dynamics — increased presence of general aviation (GA), unmanned autonomous vehicles (UAV), military aircraft in civil airspace as part of homeland defense — contributes to growing complexity of airspace. Despite continual attempts to transform the system over the years to accommodate demands, it has proven remarkably resistant to change. In fact, the feasibility of accommodating the growing ambitious objectives, such as the projected threefold increase in demand, is problematic

The problem

In addition to such traditional requirements as safety, reliability, capacity, economics, etc., a future transportation system (assuming one can design such a system) must possess a high degree of scalability. In this context we take scalability to mean that we can expand or contract the system as needed, to reach system and subsystems objectives, while maintaining constraints.

The salient feature of many complex systems, including transportation, is that they have not been “designed” in the usual sense of designing a mechanical artifact. Instead, these systems have evolved over long periods of time in response to an extensive set of demands and rules some of which we understand well and some that are not understood fully. Our goal is to develop methods that would enable active design of transportation systems, although it is not clear at the moment, which aspects of such systems are amenable to active design and which may be inherently open only to self-organizing and evolving behavior. In any case, better understanding of the phenomena that govern these systems is in order.

It is conjectured that the size and complexity of the current transportation system require a fundamental reconsideration of how such complex systems are analyzed and designed if the system is to evolve productively and remain viable. The traditional methodology for understanding large systems is based on reductionism. That is, a complex system is partitioned into smaller, manageable components. The analyses of the constituent components then contribute to the analysis of the whole system. This approach has been highly successful in science and engineering for a long time, but it requires well-posed, prescribed problem statements with comprehensive global information. However, when systems reach some threshold of complexity, the approach may no longer explain the system’s behavior. Complex, dynamic systems, such as the National Airspace System (NAS), do not appear to lend themselves completely to traditional methods based on reductionism, the latter resulting in answers that are often static and incomplete. “Emergent” (unexpected) behavior and operational vulnerabilities plague complex systems and are not necessarily derivable from component analyses. This phenomenon is exemplified by failures and unexpected behavior observed in such large systems as power grids.

Recent developments in the study of complex adaptive systems (CAS) have led a number of researchers at NASA Langley to begin preliminary investigations into the applicability of the latest developments in complex system methods to the analysis and design of alternative transportation architectures.

Modern
science
of
complex
systems

CAS and methods for studying them are inherently interdisciplinary. They focus on properties determined by complex interactions among numerous constituent elements. In contrast to traditional approaches that assume a global problem statement, CAS methods emphasize the dynamic, adaptive nature of evolving complex systems, and investigate the propagation of local subsystem effects to the systemic scale. Of great interest among CAS are networks – structures ubiquitous in sciences, biology, society, and economics. Transportation systems are networks.

The modern science of networks — including such sub-areas as self-organizing networks, scale-free networks, and dynamic networks — provides a valuable perspective for studying the dynamic and evolutionary character of networks that emerge in nature and human endeavor. Many networks that arise in different areas of science and technology have been shown to share fundamental properties. For instance, phenomena governing the propagation of cascading failures in financial networks and power grids or the spreading of disease in ecosystems can provide important insight into robustness, which is a critical attribute in CAS, and especially in transportation systems. Robustness may be viewed as a measure of the system's ability to recover from failure and maintain a stable existence over long periods. Thus, understanding of the kinds of robustness and the way in which it *emerges* in networks through *evolution* is crucial in discovering how robustness can be *designed* into the system.

The distinction between traditional analysis and design methods and CAS methods is somewhat blurred and is not static, as both areas continue developing and establishing connections. Again, a rough boundary may be stated as follows. Traditional analysis and design methods deal with systems that are amenable to relatively well-defined, global problem statements. CAS methods emphasize system complexity, dynamic behavior, and local interactions leading to global systemic effects. Realistic networks are not designed and constructed according to prescribed criteria. Instead, they grow and evolve, both in complexity and in size, through interactions among the network nodes and subsystems whose behavior is not completely determined *a priori*. Even when the individual behavior of the nodes is governed by relatively few rules, the large size of realistic networks and the changing behavior of the components result in unforeseen (“emergent”) network behavior that might not be predictable by studying the behavior of the components via traditional modeling approaches. It is precisely the global, systemic reactions of CAS to local changes in the constituent subsystems that are of interest for the purposes of effecting desired transformations in realistic transportation networks.

Complex
adaptive
problem
solving

Despite the difficulty of the task, some aspects of transportation network behavior are amenable to traditional models and methods, such as those of dynamics, control, and operations research (OR). A large body of sophisticated methods and tools address specific aspects of transportation systems, such as airline routing and scheduling over

Role of
traditional
methods

periods of time. Problems amenable to traditional tools are those for which the variables, objectives, and constraints are relatively well defined. For instance, even though a scheduling problem may be difficult to solve because it is large, given a definite number of nodes and possible routes, the attendant optimization problem is well defined and solvable for a particular time span. Applications, such as design optimization of Very Large Scale Integration (VLSI) systems and pipelines have progressed steadily. Thus traditional modeling and analysis tools certainly belong in the arsenal of network analysis and design tools. However, they do not fully accommodate the adaptive aspect of CAS, or make long-term behavior predictions, as evidenced by the inability to-date to affect significant changes in the air transportation network by using traditional approaches.

The explicit focus of CAS methods is adaptive systems that change in the number of components, the connectivity of the components, the local behavior of the components, and the rules that govern the changes during the lifetime of the system, with the ensuing global “emergent” behavior. Although some of CAS based methods have been around for a long time, modern network theory is a young field. The understanding of current network theory as related to realistic networks is largely at a theoretical and beginning stage. The tools of CAS include such methods as graph theory, agent based modeling (ABM), genetic algorithms, neural networks, nonlinear dynamics, game theory. The interdisciplinary nature of the subject manifests itself in two ways. First, it is possible to map some of the developments in a particular applied area to networks arising in other applications. Second, CAS problems are truly multidisciplinary in a sense that many disciplines (or layers) govern realistic networks. For instance, transportation systems are governed by physical and technological considerations, by economics and human factors, environmental impact, to name a few disciplines. The modern study of networks attempts to explain complex network behavior on the basis of local interactions among the network components in a multidisciplinary context.

Role of
CAS/
network
theory
tools

The challenges for CAS methods are many. Recent investigations have advanced the understanding of relatively small networks, but it has yet to address the behavior of realistically large and complex ones. The next step in the growing understanding of systemic network behavior would be the development of quantitative, predictive models in terms of application-specific variables, objectives and constraints. Thus, for applications of interest, such as transportation networks, one has to map the terminology of network theory to the quantities of interest, such as robustness, safety, sustainability, affordability, etc. Moreover, the ability to design and optimize realistic networks is of ultimate interest. Such design methods have yet to be developed. The ability to analyze and predict network behavior is a necessary step on the road to developing design methods. It is not clear to what extent predictive modeling is possible.

Given the extremely challenging problem of affecting transformation in the existing transportation system to accommodate growing demands in capacity, safety and other objectives, as well as the recent developments in CAS methods, NASA LaRC and NIA organized a workshop intended as a forum for exchanging ideas and establishing an initial working group for the study of transportation networks. The workshop’s

Workshop
highlights

deliverable will serve as input to the roadmap for NASA and NIA research guidance under development at NASA LaRC.

The workshop participants were asked to consider the following main questions:

- What is the state of the art in modeling and design tools for current transportation systems and what is the role of traditional methods vs. modern CAS methods? What is missing?
- What kind of a network should a transportation system be in terms of the type of topology (type of network), controllability, robustness, and other aspects?
- How do we go from the theoretical analysis of networks to designing networks for practical, applied objectives (e.g., reliability, cost)?
- What are the subproblems of most practical interest in the general taxonomy of problems that we can address in the near future?

Initial intensive discussions brought about the following consensus:

- Methods and tools exist that are relevant to the problem of analysis and design of transportation networks, but the existing tool set is incomplete.
- Defining the problem is critical. Tool definition will emerge from problem identification.

Given the need to set the problem boundaries, the participants focused on the general question *What Is the Problem?* and the specific question of modeling the system for the remainder of the workshop. Some highlights of the discussion follow. (Discussions are reported in detail in the body of the proceedings.)

- What do we need to model?
 - It is important to attempt to capture the entire transportation system in all its complexity, starting with low-fidelity representations of the components. Being able to characterize the present system is necessary for validation, for the ability to affect changes, and for determining whether a particular topology (e.g., scale-free networks) is a good model for air transportation to emulate.
 - Models need to include demand modeling to determine demand side effects, equilibrium analysis, and network topology. They must emphasize safety and reflect drastic behavior changes. Large-scale, simple models are needed to consider trade-offs between policy, technology, and procedures and to provide guidance for future investments. Transportation topology models must also include vehicle characteristics.
 - Models must be adaptive and allow for interpretation of the significance of the results.
 - Models must include other transportation modes.
- Difficulties in modeling
 - Existing traffic management models are usually static, encompassing short time periods, although some models in OR cover longer time periods. In

general, models are not adaptive in that they take demand and capacity and run against each other, but difficulties result in flight cancellations. The airlines plan far in advance and are limited by their plans.

- Existing models are rarely predictive and they lack validation and verification. Use of different models sometimes leads to diametrically opposed predictions.
- There are many modeling activities (e.g., in airlines and FAA), but they lack coordination and it is not clear what is missing in each model or tool.
- Any single representation of the system may be infeasible. It depends on the perspective of the system builder (traveler, airline, etc.)
- What does a transformation require?
 - Supply / demand transformation for air transportation systems with respect to customers, suppliers, regulators, and market dynamics;
 - Ability to determine and scale up the level of participation, routes, facilities for existing companies;
 - Scenario evaluation/assessment capability;
 - Assessment of the effects of privatization.

The discussion emphasized the need for accommodating the dynamic and adaptive nature of realistic transportation systems and thus investigating CAS-based tools, such as ABM and game theoretic approaches.

The need for extensive literature search, comparisons with other network-related applications, and adopting lessons already learned in other applications, such as biology and computational networks, came up repeatedly. Investigations into the operational side of transportation systems (pilots, controllers, etc.), policy issues, as well as inquiries into the experience of other countries and future planning information from industry were proposed. A common theme was the need for in-depth understanding of existing models, their attempted domain and range, and how they succeed or fail in representing a particular aspect of the system. Fundamental questions of what can be learned from scale-free and other network structures as well as the ability to capture the evolving nature of the system were raised repeatedly. These questions can be summarized as a proposed inquiry into understanding the network topology and its dynamics.

The participants found the exchange productive. The proceedings and the collected bibliography are available to all interested researchers. The workshop has established an initial working group with a particular interest in transportation systems. The next step involves defining specific problems for near-term study, continued building of collaborations and teams, and continued development of the roadmap for systematic research on transportation networks.

Where
do we
go
from
here?

Natalia Alexandrov
n.alexandrov@nasa.gov

WORKSHOP OBJECTIVES

The existing air transportation system is reaching the limits of its capacity in a number of ways. Mobility, throughput, customer satisfaction, safety, security, communications, fuel consumption and other ecological demands are some of the major problematic aspects of the current system that must be addressed in the increasingly complex and populous world.

Transportation systems, such as airports connected by routing via the National Airspace System (NAS), are networks of great practical interest, but our understanding of their dynamic behavior is limited. Current analysis techniques of transportation systems are often static and incomplete. With some notable exceptions (e.g., the design of VLSI, pipelines, scheduling), the design of complex networks with respect to objectives of applied interest is at an embryonic stage. As with other systems, improvements in the transportation systems will rely on the existence and maturity of two basic components: analysis and design.

Recent developments in the study of complex systems and network theory, in particular, have led a number of researchers at NASA LaRC to begin preliminary investigations into the applicability of the latest developments in complex system theory to the analysis and design of alternative transportation architectures. The workshop is intended to serve as a forum for exchanging ideas and establishing an initial working group for the study of transportation systems. The following questions are offered for consideration to the workshop participants (the list is not exhaustive):

- What is the state of the art in modeling and design tools for current transportation systems?
- What aspects of transportation systems are amenable to traditional analysis and design methods, e.g., to the methods of operations research?
- What aspects of analysis and design of transportation systems are not amenable to traditional approaches and require the application of emerging methods or the development of novel methodologies? Can we identify critical tools and methods, either existing or requiring development, for the analysis of realistic transportation networks?
- It is important to map the developments in complex system theory (e.g., network theory) to transportation problems. What is the best or feasible way for developing such a mapping with an attendant dictionary (“lexicon”)? Can we learn from similar activities in other applications?
- What kind of a network should a transportation system be? For instance, scale-free networks have a number of attractive characteristics, such as high degree of connectivity and consequently a high degree of robustness with respect to some objectives. However, their structure also makes scale-free networks vulnerable to catastrophic failures. Assuming that we can design hybrid networks, what are the desirable properties of a transportation network?
- How much uncertainty can be tolerated in a transportation network? Or, in other words, how much controllability must a network have? Highly complex systems

may exhibit unpredicted (“emergent”) behavior. How can we account for such behavior? Does the need for controllability imply that we are necessarily limited to certain types of network topologies?

- How do we translate designing networks for theoretical objectives (e.g., connectivity) to designing networks for practical, applied objectives (e.g., reliability, cost)? How do we map theoretical network entities to variables, objectives, and constraints of use in defining the applied design problem?
- How do we estimate the time and effort required to develop methods and tools for realistic transportation network design in all its complexity?
- Given that we will not be able to handle the analysis and design problem in all its complexity for a long time, what are the subproblems of most practical interest that we can address in the near future? Can we establish a taxonomy of subproblems whose solutions will be of value and will advance the state of the art on the road to overall transportation system design?
- What are clear, simple cases for which we can compare various simple transportation topologies and which can be used for the development of methodologies?
- What are the potential collaborations?

In summary, the workshop aims to examine the feasibility of applying traditional methods for complex system analysis and design as well as potential novel alternatives in application to transportation systems, identify state-of-the-art models and methods, identify methods and tools that have yet to be developed, and thus to lay a foundation for establishing a focused research program in complex systems applied to air transportation.

PARTICIPANT INTRODUCTIONS

This section reports on the brief introductions made by the participants at the workshop, some ensuing discussions, and the post-workshop input requested from the participants.

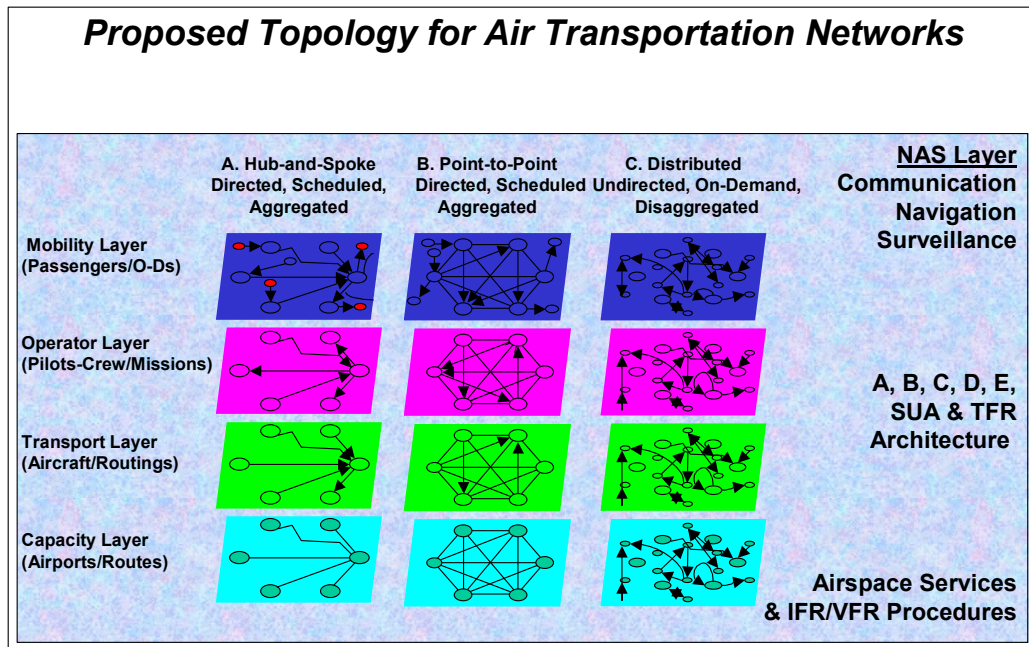
Bruce J. Holmes (Associate Director for Airspace Vehicle Research, Airspace Systems Programs Office, NASA LaRC)

The workshop started with an introduction from Bruce Holmes who leads strategy development for the aeronautics programs and competencies at NASA Langley and serves at the Next Generation Air Transportation System Joint Planning Development Office (JPDO), supporting development of the National Plan for Transforming the U.S. Aviation System.

The introduction focused on the complexity of air transportation topology illustrated in the figure on the next page (see “Network Theory: a Primer” [1] in the Appendix of the proceedings). The *mobility layer* deals with passenger demand and throughput; the *operator layer* is concerned with pilot crews and missions; the *transport layer* deals with

aircraft and routing; the *capacity layer* has to do with airports and routes; finally, the *NAS layer* deals with communication, navigation and surveillance.

In the context of these layers, one might consider a range of topologies characterized by sets of attributes. Directed, scheduled, aggregated topologies may be exemplified by the hub-and-spoke system (A) and the point-to-point system (B). At the other end of the



spectrum lie distributed, undirected, on-demand, disaggregated topologies (C). One might envision other topologies or hybrids. Analyzing unconventional topologies, such as C, presents many difficulties: while it is relatively easy to describe risk in A and B to customers, it is very difficult to describe risk in C; in C topologies design requirements come from network behavior (this feature is not pronounced in A and B); network operations have very subtle but strong consequences for the operation of the fleet; subtle changes in aircraft have dramatic effects on network performance. We have not accounted for these types of behavior in the present systems, but some projections predict increased future requirements for point-to-point, on-demand transportation, even for intercontinental travel.

Bruce also introduced the notional Transformation Concept Space – a notation for representing the contributing transportation components in the total transportation system, according to the topological attributes. The aim of the activity undertaken by JPDO is to expand the transformation concept space along all dimensions. Considering the complexity associated with analyzing, comparing, and designing air transportation

topologies, we have to arrive at a roadmap that will assist in focusing research in practical directions.

Discussion:

Q: Is the purpose of the roadmap to inform policy or is it to provide a plan for development?

A: The roadmap is to assist NASA and NIA in developing a research program framed by the JPDO goals of safety, affordability, security, and other goals.

Q: The words “scalability” and “scale-free” are used often but the meaning is unclear. For instance, they are frequently used interchangeably. What exactly is meant in the context of air transportation?

A: “Scalability”, as a desirable characteristic in the context of these discussions, means the ability of a transportation networks to accommodate a growing number of nodes without degradation of network performance. It means “affordable”, “easy to adapt system to growing changes”. “Scale-free” in the context of networks means that the distribution of the nodes of a network obeys the power law.

Comment: Because these are important concepts, we should use the words “scalability” and “scale-free” more precisely. Perhaps, introducing more descriptive terms is in order.

Comment: We need to consider systemic impacts of changes in transportation systems. For instance, point-to-point on-demand topologies may require more airplanes, but fewer buses and trucks may be required as a consequence. Ergo, *we must establish the boundaries of the transportation system under consideration.*

Comment: A related and important question is the *range of applicability of tools and methods*. Traditional tools may not suffice to assess limited effects of local changes. May have to look to novel approaches for propagating the local changes throughout the entire system dynamically. *What are the frontiers in methods? Where do current methods fall short?*

Natalia Alexandrov (Senior Research Scientist, Multidisciplinary Optimization Branch, Aerospace Systems Concepts and Analysis, NASA LaRC)

Current interests include multidisciplinary optimization of complex physical systems (MDO), modeling of large-scale distributed complex systems, modeling and model management in optimization of systems governed by partial differential equations.

Natalia became interested in CAS as a complementary approach to traditional modeling and nonlinear programming techniques in posing and solving realistic design problems. She is also interested in problem definition and modeling for transportation systems with the eventual aim of developing design-oriented analysis techniques and design methods. Natalia and Kurt Neitzke are co-principal investigators of a JumpStart project (part of the

NASA Langley Creativity and Innovation program), the objective of which is the development of a roadmap for systematic research in transportation systems.

Natalia presented the questions for consideration to the participants (see Summary and Workshop Objectives). Workshop materials and some CAS related links are accessible from <http://mdob.larc.nasa.gov/natalia/networks>.

Cynthia Barnhart (Professor, Department of Civil and Environmental Engineering, MIT)

Cynthia has worked extensively on the design of networks for transportation operations, especially in the airline industry. “I am particularly interested in scale-free networks because I am interested in investigating how we might cast our optimization models to generate scale-free, robust networks for transportation operations. I am also interested in understanding better the relative robustness of these networks and the cost of robustness.”

Cynthia is a co-director of the Center for Transportation and Logistics at MIT. Some of Cynthia’s publications in network design modeling and solution algorithms are [2–6]. She is participating in the sustainable network initiative, a global airline industry project at MIT, the details of which can be accessed from Cynthia’s web site at <http://web.mit.edu/cbarnhar/www/cb.htm>.

Sheila Conway (Research Engineer, Projects and Advanced Concepts Branch, Airborne Systems, NASA LaRC)

Sheila's background is in aircraft design, piloting and operations development. Currently, her primary focus is strategic air traffic and airspace management, and the proper balance between centralized and distributed control. In her words, “Having worked in this area for a few years, she has developed a healthy cynicism towards comprehensive modeling efforts, but is still hopeful. Network modeling is one of many tools that may prove to be useful for system-wide dynamic behavior analysis.”

Daniel DeLaurentis (Visiting Assistant Professor, School of Aerospace Engineering, Georgia Tech)

Dan is a co-leader in the advanced design methodology thrust area for the Aerospace Systems Design Laboratory (ASDL). His recent research interests include methods for problems characterized as system-of-systems (especially in transportation), robust design for aerospace, and numerical and visual tools for capturing the interaction of system requirements, concepts, and technologies. The context for these activities has been the design of revolutionary air vehicles for which present sizing/synthesis models are incomplete, e.g., uninhabited air vehicles (UAV). Several recent projects illustrate the extension beyond individual vehicles to the design of systems of vehicles.

Dan has participated in interdisciplinary projects, such research on neural-network-based technology prediction and a project involving the development of design for affordability.

Dan's introductory charts are in the Appendix. Some of his publications related to the workshop's themes are [7–9]. Dan recommended a recent study by RAND on Long Term Policy Analysis at <http://www.rand.org/publications/MR/MR1626/>.

**Joe W. Elliott (Facility System Safety Engineer, Office of Safety, Security,
Environment and Mission Assurance, NASA LaRC)**

Joe's background is in Mechanical Engineering and Engineering Administration. His experience is in the areas of strategy and strategic planning, program management and planning, system engineering, system modeling, decentralized systems, and social behavior. Joe is interested in "Using the appropriate tools (from above) to better understand, and elegantly solve real world problems".

**Roger Guimerà (Post-Doctoral Fellow, Department of Chemical and Biological
Engineering, Northwestern University)**

Roger's research is devoted to the application of statistical and computational physics to the study of complex networks. He is interested in both static-topological and dynamical aspects of networks in physical, biological, ecological, technological, and social systems. His work on air transportation networks and on optimal communication networks is particularly relevant. Some references related to the workshop themes are [10–13]. More publications can be found on the group site at <http://amaral.northwestern.edu>.

Roger emphasized that in airport networks, what matters is not just high connectivity, but also centrality and therefore the frequency of use. There are highly connected nodes that are very important because of their centrality.

**Pamela Haley (Research Engineer, Dynamics and Control Branch, Airborne
Systems, NASA LaRC)**

Current research interests include adaptive control (particularly generalized predictive control) in autonomous vehicles and the potential application of network dynamics to systems of autonomous vehicles. Past research has focused on the application of generalized predictive control methods to reconfigurable control and aeroservoelastic control.

Rex Kincaid (Professor, Department of Mathematics, College of William & Mary)

In Rex's words, "Pertinent research interests of mine are network location theory and metaheuristics for optimization models (primarily discrete ones). I am most familiar with simulated annealing, tabu search and evolutionary search strategies. The applications of these metaheuristics have included the location of both sensors and actuators on aircraft and flexible space structures as well as the location of points on a graph required to meet a variety of performance measures."

"I spent last summer reading about scale-free networks. During that time I duplicated various computational experiments with regard to the generation and formation of scale-free networks. I am teaching a course on scale-free networks this spring at William and Mary." Some of Rex's work related to networks is in publications [14–17].

Michael Kuby (Associate Professor, Department of Geography, Arizona State University)

Michael is a transportation geographer who specializes in optimization models for transportation and facility location problems. Most of his work has integrated technology choice with location decisions and network design in recognition of the interdependencies among these decisions. In the air transport field, his paper on the hub network design problem with stopovers and feeders developed a model for simultaneously optimizing network structure and aircraft type. His other research—much of which has utilized multiobjective optimization—has focused on energy delivery systems, railway network design, waste system management, and hydrogen vehicle refueling infrastructure. Some of Michael's work related to the workshop topics is referenced in [18–21].

Michael believes that modeling the entire transportation systems in a single model is not a practical undertaking. He recommends considering the National Energy Modeling System (NEMS), a system of linked models that together model "the whole thing". DOE uses NEMS to predict future developments in the energy industry and markets, but many of the submodels are themselves optimization models. DOE has accumulated 30 years of experience in modeling "the whole thing" and is a good place to start investigating large models. Michael has been a reviewer and consultant on DOE coal models.

Michael also recommends considering the work of Getz (University of Denver) and O'Kelley (Ohio State University) that deals explicitly with air transportation geography.

Phillip Lederer (Professor, William E. Simon Graduate School of Business Administration, University of Rochester)

Phillip's background is in operations research and his current interests lie in combining operations thinking with economic modeling. Phillip is also interested in consumer demand side and day-to-day operational failures of transportation networks. Some of his

work in network topologies is in publications [22–24]. Phillip’s introductory charts are included in the Appendix.

Kurt Neitzke (Senior Systems Analyst, Systems Analysis Branch, Aerospace Systems Concepts and Analysis, NASA LaRC)

In Kurt’s words, “My interests with respect to complex systems and network theory lie principally in seeing if a promising modeling technique for air transportation can be developed in this area. We are always looking for new ways to model air transportation that will better equip us to answer questions from Headquarters strategic decision makers and Program/Project Managers in relation to technology impacts on the system.”

John Scott (Director, Defense and Government Services, Icosystem Corporation)

Icosystem Corporation is a research and consulting firm based in Cambridge, MA, (with offices in Washington DC, Silicon Valley and Houston, TX) that develops platforms to systematically identify opportunities within complex systems, and then designs strategies or interventions to realize those opportunities.

In John’s words, “The company scientific and technical staff includes a number of the world’s leading experts in the areas of Swarm Intelligence (distributed adaptive problem solving), Complexity Science, Robotics and Evolutionary Computation. Icosystem clients include Fortune 100 clients as well as ONR, DARPA, DISA and OSD-NII, to name a few. We are interested in the application of agent-based modeling and network design for the purposes of creating a more robust national air-transportation system.”

John refers the participants to publications [25–28]. He recommends that modeling the transportation system start at the high level of modeling the specific policies that govern the NAS. This would lead to a better understanding of what policies are important. John comments that the software for modeling the entire transportation system is very limited and any good ABM must be constructed from the bottom up.

Marie Stella (System/Security Engineer, Federal Aviation Administration)

Marie is on detail to the Center for Technology and National Security Policy (CTNSP) at the national Defense University, focusing on information assurance issues. She organized the recent (8 December 2003) workshop on Complexity and Shared Critical Infrastructure Vulnerabilities for Cyber Conflict Studies Association/NDU and co-chairs NASA Security Workshop of Annual *i*-CNS Conference. She is an independent evaluator and COTR for ARDA research and the lead Security Engineer for FAA Communication IPT, as well as the former lead System Engineer for Traffic Flow Management.

Marie's interest in the workshop is due to her "Belief in aviation industry as major economic driver and that another physical or a cyber attack would be deleterious to our national security" and concern "that we are underestimating new or unknown threats and vulnerabilities in current operations and under higher usage and higher stress conditions". She is also concerned with "Safety and security implications of interdependencies, shared infrastructures, and inability of leaders to take a holistic look at the airspace and its multiple sub-systems, including: National-International, Business Partners, and DOD Homeland Security sub-networks; changing air space environment, such as UAV, Sonar and Sub-Sonar traffic, aircraft warfare countermeasures, etc." Marie is interested in surfacing "need for life-cycle analysis to manage and maintain countermeasures and to look at different approaches to robustness that may include self healing, quarantine and other techniques to restore systems under attack."

Marie outlined the following needs:

- The need for research funding increase;
- The need to develop scenarios that challenge current and future network (airspace and technical system base) and take into account network complexity and emergent vulnerabilities;
- The need to simulate, model, test concepts, robustness, flexibility, restoration capabilities of NAS and underlying infrastructure by using new model paradigms that include gaming and behavior models;
- The need to have a dialogue for shared ideas between infrastructures – with government, industry and academia;
- The need to "leverage research activities to get best bang for small budget and to influence political thinking in the understanding of complexity".

Sean Tierney (Graduate Student, Department of Geography, Arizona State University)

Sean is a transportation geographer with interests in airline network design, airports, and Geographic Information Science (GIS) applied to transportation.

Antonio Trani (Associate Professor, Department of Civil and Environmental Engineering, Virginia Tech)

Toni's interests are in air transportation, simulation and modeling, airport engineering, systems engineering, and infrastructure systems. He was able to participate in the workshop briefly, on the second day. Tony highly recommended reference [29] as a comprehensive summary of challenges facing the air transportation system.

Marty Waszak (Research Engineer, Dynamics and Control Branch, Airborne Systems, NASA LaRC)

Current research interests include application of complexity science to autonomous collaborative control of flight vehicles including decentralized control, self-organization, agent based modeling and simulation, and network dynamics. Marty is also interested in understanding how operational context influences vehicle requirements/capabilities and vice versa (i.e., the interaction between vehicle systems technologies and airspace systems technologies). Past research has focused on stability and control of micro aerial vehicles and dynamics and control of aeroelastic systems.

Leonard Wojcik (Lead Staff, Center for Advanced Aviation System Development, the MITRE Corporation)

Len is a researcher at MITRE Corporation and the MITRE liaison to the Santa Fe Institute. His work includes NAS system-level modeling that considers system-level impacts of new technologies, airports, etc. on transportation systems.

Len has also worked on agent-based and game-theoretic modeling of decision-making in air traffic flow management (TFM) [30–33]. In this work, airlines and other players are modeled as independent, self-interested agents, and the systems are allowed to evolve spontaneously. The model worked in two time frames: one day and years. Bayesian decision analysis of TFM events was also done. Reference [36] deals with assessing decision-making under uncertainty in traffic flow management events.

Len has worked on Travelscape, a future concept for empowering passengers to participate more fully in the traffic flow management process (there are no papers on this topic yet, but a publication is expected in the near future). Len suggests references [34–35] for work on ABM of the evolution of the whole system of airlines (Jet:Wise).

In reference to the domain of applicability of traditional vs. new methods, Len comments: “I think traditional OR techniques and tools are applicable as long as we know the characteristics and bounds of our system. Systems dynamics models (e.g., the “NAS Strategy Simulator” being developed for FAA ASD via Vensim [software]) may be applicable to address very broad relationships and tradeoffs, again as long as we can fully specify the characteristics of the system. For very broad analyses, such as what we are attempting here, validation of such models can be very challenging and is likely to be an issue. Where the characteristics of the future system are unknown (as applies to our problem), a “generative” model may be more appropriate. Generative models include agent-based models and models based upon solution-space-spanning optimization heuristics like genetic algorithms and simulated annealing. Validation is a significant challenge for these kinds of models. However, in an exploration like we are doing here, validation may be very limited in any case.”

On modeling transportation systems: “I think it might be worthwhile trying several approaches to model the future aviation network, including exploration of the solution space with optimization heuristics and agent-based models, as well as non-generative approaches like systems dynamics modeling. Models of sub-elements of the NAS should be simplified as necessary, but to the greatest extent possible the key network elements should be kept in (including the capability to represent demand-tripling), as well as the criteria of interest (safety, efficiency, reliability, environment, etc.). This is tricky, because if it's too simple, there won't be enough substance to get anything interesting, but if it's too complicated, progress will be too slow. Ideally, the modelers should address the “whole” problem, but in a relatively simple way, and get some provocative initial results. As the modeling attempts progress, I suspect it may become necessary to pull back on the requirement to model the whole problem, but that should be the starting intent.”

On the availability of models: “MITRE has various models and tools that may be of interest. A model of an overall network of flights is DPAT (see "The DPAT User's Manual", F. Wieland, MITRE MTR99W0V0S0R12, August 1999 for basic functional information about this model), which is often used in conjunction with the Future Demand Generator (FDG), to model future traffic scenarios. An agent-based model of airline evolution is Jet:Wise, which is cited above.”

BREAKOUT SESSIONS

A consensus emerges:

- Relevant methods and tools exist, but the tool set is incomplete.
- Until we define the problem more precisely, we cannot answer questions about tool usability and identify what has to be developed.
- Tool definition will emerge from problem identification.

A reminder of the goal: We would like to develop a roadmap for NASA and NIA research guidance framed by JPDO goals (timeframe is 2025). This implies defining problems and challenges and a gap analysis of tools and solution methods. We proceed under the following assumptions:

- It is possible to create a system that will accommodate and stimulate future development.
- The demand will triple.
- Consumers will choose.
- The conjectured network objectives are maximization of profit, robustness, and minimization of infrastructure cost.

The participants spend the remainder of the day in two groups working on specific suggestions that will answer the following questions about the problem statement:

- What are problems, subproblems (taxonomy) and tools for studying the space of transportation network objectives that will take into account the goals of policy, technology and business models for complex, adaptive ecosystems?
- Can the existing methods answer the question: Do sufficient resources exist (pavement, airspace, spectrum, etc.) to handle a threefold increase in demand?
- How would the approaches be applied?
- Can we identify the frontiers in transformations where traditional tools will fail? That is, where does the emergent behavior begin?
- Where do existing methods fall short and how do we provide guidance for new tool development?

Results of Breakout Session 1

Group 1 (Natalia, Alexandrov, Joe Elliott, Rex Kincaid, John Scott, Marie Stella, Sean Tierney, Marty Waszak, Len Wojcik) attempted to answer the question “*What is the problem*” and focused on modeling.

- What do we want to model?
 - NAS traffic;
 - All layers in Bruce’s proposed topology.
- Difficulties in modeling
 - Existing traffic management models are static, encompassing from a couple of hours to a few days, not dynamic and strategic. Models are not adaptive in that they take demand and capacity and run against each other, but if an airline has problems, it will just cancel the flight. (Len)

Comment: There are models in OR that cover much longer periods of time (Mike and Sean)

General discussion: Need a model that can be worked into operations. Need an adaptive tool that can be used for many scenarios. One could end up with a model that is stretched so far that one cannot interpret the significance of results.

- Based on experience, use of different models can result in diametrically opposed answers and recommendations; need an activity in model validation; need meetings with other groups that develop models (Marie)
- Can learn lessons from Perelson's HIV virus model development: sometimes simple models are good enough. They can reveal fundamental interactions that dominate the overall behavior of a system that can be masked in more detailed models. The insight and understanding obtained from simple models can provide direction and guidance for more detailed studies. (Marty)
- Essential to develop predictive, validated models with an established range of applicability. Predictive models are necessary for the eventual

introduction of design, not just analysis of transportation systems.
(Natalia)

- Need to consider game theory, ABM, and other modeling approaches.
(All)
- How do we decide on weights in the weighted combinations of topologies? (Joe)
- We need to look at the feasibility of all these topologies. Transformation of the air transportation system alone may or may not be best. Need to include other modalities in modeling mobility. (Rex)
- Our problem statement is too general: Develop methodology and tools for the design of transportation systems for a specific set of objectives.
- How do we actually go about realizing a transformation?
- A transformation requires
 - Supply / demand of transformation for air transportation system with respect to customers, suppliers, regulators, market dynamics
 - Ability to determine and scale up the level of participation for companies in new routes and facilities
 - Because Solutions may lie not in airspace alone, but a mixture. Need to give answers in terms of mixed investments (e.g., air and ground or something else)
 - Scenario evaluation/assessment capability
 - Assessment of the effects of privatization
 - Starting from existing system and “growing” a new capability with better performance
- Question: Can we model the current system?
- Last words:
 - Start simple and capture the “whole thing” with simple representations (Len)
 - Bias toward breadth over depth in defining both the analysis and design problem (Natalia)
 - Descriptive model of current state of affairs in aviation (Sean)
 - Need a baseline model; need to reflect drastic behavior changes in the model; have NASA take on a task of model validation; latest trends in modeling, perhaps outside of aviation; assess effects of changes to existing NAS (validating sensitivity analysis) (Marie)
 - Joe: How does “network” get into it air transportation? What are the limits to what the government can/should do (as opposed to industry)? (Joe)
 - Need simple, large-scale modeling to look at trade-offs between policy, technology, procedures; guidance for future investments in general (John)
 - Emphasize the dynamic and adaptive nature of the system (Marty)

General discussion:

(Joe, elaboration on the government role) A web search revealed a lot of model development already under way in the government and industry. We need to understand what already exists before embarking on further development. We should consider bringing in the economics and the personal choice factor. The government did not create the hub-and-spoke or point-to-point system. They were created by the enterprises that make decisions based on their economic worlds. We must consider how much the government can impact what the private industry will and will not do.

(Marie) Many models have been worked on over the years and were not successful. We need to spend time figuring out what pieces are missing that made the previous studies fail. We need to go back and validate the models that were developed and used previously. We may find out that free flight cannot work because there are too many variables and the models may not operate as expected.

Results of Breakout Session 2

Group 2 (Cynthia Barnhart, Sheila Conway, Daniel Delaurentis, Roger Guimerà, Pamela Haley, Michael Kuby, Phillip Lederer, Kurt Neitzke) concluded that a prospective air transportation system model should include the following characteristics:

1. Need to include demand modeling (Phillip) – to determine demand side effects, equilibrium analysis, network topology modeling; put the two together and see what falls out.
2. Networks, vehicles, simulations, scenarios—it is not just the network topology, but the vehicles which are the links—the vehicle characteristics that make those links is a big part of the equation. Also consider the policies that the regulatory agencies supply that determine how the vehicles operate within the environment.
3. Can we get a network optimization or simulation to form a scale-free network (Roger)? Key is to understand what the network would look like.
4. Characterize the type of network we have now (Roger): airline routing networks and aggregate routing networks
5. Need to understand (explore whether the networks would be scale free if other aspects were considered, say, if aggregated by airline) the temporal nature of node connections (i.e., no “hard wiring” of nodes, but rather planes flying between airports).
6. How will on-demand transportation affect the network topology?
7. What economies of scale result from the distributed on-demand system that Bruce proposed? Or, rather, how do economies of scale impact network topology? Consider seat-miles cost, comparison of flying a big plane empty vs. small plane full. Discuss the growth of regional airlines and the fleet changes; influenced by the frequency of service and getting passengers to big airline hubs.
8. Why do scale-free networks evolve (Roger)?
9. Is a scale-free network topology a good model for air transportation to emulate (Roger)? (Sub-problem of #3).

(Items 3-5, 8, 9 are related.)

Discussion: Models are supposed to be creating good transportation networks. One can learn more when models do not match reality by trying to understand the implications of what the models lack.

Would networks be useful for discovery of interstitial connectivity between layers from Bruce's scenario (Sheila)? A lot of modeling is going on (airlines, FAA, etc. – What are some of the things that these groups are missing?)

10. Role of agent-based modeling? (Kurt)

Discussion: What kinds of solutions do we want – centralized, global – or some simple sets of rules that would allow airlines to operate on their own. Is the network going to be dynamic? Deciding which way to do this will play a significant role in the outcomes.

CONCLUDING REMARKS

(Len) Get a more in-depth understanding of existing models and what they were attempting to cover. It would be beneficial to do a first cut at a rough level (within the next few months) of the whole thing. That would keep us focused on the whole problem, and help identify what needs to be done.

(Kurt) Big question: Is the network theory going to be useful to us in terms of defining better airspace use or helping us to decide which technologies we should be designing and developing?

(Natalia) Interested in trying to find tools one can experiment with rather than big, black box codes systems. We would like these for conducting research and for passing along to universities.

(Phillip) It would be useful to look at different literatures and hear different perspectives.

(Sean) From a geographer's perspective: the use of GIS might be a very powerful tool/concept to use on existing models to help get a good understanding of how these things are progressing.

(Mike) A thought on how to model this whole transportation thing: Strategy 1 – separate the models of each part and build links between. Strategy 2 – an endogenous model of all four layers (a la Bruce's chart).

(Cynthia) It is important to try to figure out how to capture the system-wide picture at whatever fidelity is available. Optimistically – could there be a new kind of planning paradigm here? As sophisticated as the tools are, we are missing something. Interested in looking at whether we can learn something in scale-free and other network structures.

Can we capture the evolving nature of the system? It is very important to continue the connections that we have created.

(Marie) Want to suggest a new paradigm in thinking about air transportation. As we look at changing airspace models, we consider the safety in the airspace. Maybe some gaming models would be appropriate – behavioral models, and more. We are doing something very different in our way of thinking about this. A lot of the airspace we are looking at reminds one of automated warfare (humans cannot react as fast, etc.) It appears that no one knows about the boundaries of air traffic control; would be good to have someone come in during next workshop or conference to talk about what is going on in the minds of the controller during the course of a workday. We would like to hear similar information from a pilot.

(Sean) Two big issues: understanding of network topology and understanding the dynamics of network topology.

(Sheila) Perspective: Any single representation of the system may be infeasible. It depends on the perspective of the system builder: traveler's perspective, airline perspective, etc. Want to discuss how these different perspectives give us insight into what we are creating.

(Pam) Leaving with the important thought that it is all about the modeling. One cannot do anything until more comprehensive models are developed. Would like to see study of what's out there, what exists, limitations and capabilities – and go from there. Another thought – maybe start from scratch – use agent-based or game theory modeling to see what would evolve and see how it is different from what we have now.

(Toni) This is a very difficult challenge. Can learn from work of people developing very large-scale models (Federal highway development does long-range planning). Los Alamos researchers say that modeling behavior of people is much more difficult than modeling nuclear reactions. Our big challenge is human behavior – how people make choices, how they perceive safety. Very exciting time, hope we can continue. Also hope that Bruce/JPDO – becomes the one agency that acts as the central repository of some of the models being developed.

(Rex) Perspective: an eco-system. That perspective captures the idea that the network encompasses many different aspects and characteristics. Need to be clear on the terminology, should get a common lexicon. Know nothing about policy decisions – may be artifacts of the current system that, with tweaking, might create openings for others to attempt innovations.

(Joe) Multidisciplinary approach: Benefits come at the intersection of the many disciplines. Include someone from the VAMS project. Initiate short-term projects for NIA. Need to continue the dialogue initiated at this workshop, especially Bruce's insight into the JPDO work.

(John) We would like to hear more from operational side of house (airline pilots, controllers, etc.) What would they find useful? Investigate what other countries are doing (e.g., China). On the modeling side, need to include demand, quality of services, long-term effects of population.

(Dan) Agree with all. Transformation is the key word. We will learn a lot from the examination of existing models. Insight is to be gained by looking at the holes in the existing models. Modeling will allow us to arrive at insights that we would never be able to achieve. The neat thing is that the models allow us to look at business models, adaptive characteristics, etc.

(Cynthia) Models are highly sensitive to demand. Can we figure out how to build a system that can be more responsive to information? The airlines plan very far out and then are stuck with what they plan. Demand adaptability.

(Marie) Considering automation systems (not topology), what are the scenarios we would examine in the case of an attack? Do we isolate parts of NAS, shut down computer systems, etc.?

(John) Need information on policy and how the government controls NAS. Which policies change when the external environment changes?

(Sean) We would like to get more future planning information from a company such as NetJet or JetBlue.

(Bruce) It is easy to feel naive. This is one such situation, but it is all right – working in interstitial areas means that advances come in the intersections. Feel inspired! We have just created a network of people who as a group can work on the future transportation models.

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PARTICIPANTS' CONTACT INFORMATION

Dr. Natalia Alexandrov
Mail Stop 159
NASA Langley Research Center
Hampton VA 23681-2199
757-864-7059
n.alexandrov@nasa.gov

Prof. Cynthia Barnhart
Engineering Systems Division
Massachusetts Institute of Technology
77 Massachusetts Avenue
Building 1-229 A/E40-149A
Cambridge MA 02139
617-253-3815
cbarnhar@mit.edu

Ms. Sheila Conway
Mail Stop 152
NASA Langley Research Center
Hampton VA 23681-2199
757-864-5564
s.r.conway@larc.nasa.gov

Dr. Daniel DeLaurentis
Department of Aerospace Engineering
Georgia Institute of Technology
P.O. Box 0150
Atlanta GA 30332
404-894-8280
dan.delaurentis@ae.gatech.edu

Mr. Joe Elliott
Mail Stop 429
NASA Langley Research Center
Hampton VA 23681-2199
757-864-9533
j.w.elliott@larc.nasa.gov

Dr. Roger Guimerà
Chemical and Biological Engineering
Northwestern University
2145 Sheridan Road
Room E-136
Evanston IL 60208
rguimera@northwestern.edu

Ms. Pamela Haley
Mail Stop 132
NASA Langley Research Center
Hampton VA 23681-2199
757-864-1705
p.j.haley@larc.nasa.gov

Dr. Bruce Holmes
Mail Stop 264
NASA Langley Research Center
Hampton VA 23681-2199
757-864-6043
b.j.holmes@larc.nasa.gov

Prof. Rex Kincaid
Department of Mathematics
College of William & Mary
P.O. Box 8795
Williamsburg VA 23187-8795
757-221-2038
rrkinc@math.wm.edu

Prof. Michael Kuby
Department of Geography
Arizona State University
Tempe AZ 85287-0104
480-965-6850
mikekuby@asu.edu

Prof. Phillip Lederer
William E. Simon Graduate School
of Business Administration
University of Rochester
Rochester NY 585-275-3368
lederer@simon.rochester.edu

Mr. Kurt Neitzke
Mail Stop 248
NASA Langley Research Center
Hampton VA 23681-2199
757-864-4917
k.w.neitzke@larc.nasa.gov

Dr. John Scott
Icosystem Corporation
10 Fawcett Street
Cambridge MA 02138
240-401-6574
johnscott@icosystem.com

Ms. Marie Stella
Center for Technology and National
Security Policy
National Defense University
Building 20, Suite 1
Ft. Lesley J. McNair
Washington D.C. 20319-5066
202-685-3046
stellam@ndu.edu

Mr. Sean Tierney
Department of Geography
Arizona State University
Tempe AZ 85287-0104
480-965-7533
sean.tierney.1@asu.edu

Prof. Toni Trani
Department of Civil and Environmental
Engineering
Virginia Polytechnic Institute and State
University
301-P Patton Hall
Blacksburg VA 24061
540-231-4418
vuela@vt.edu

Mr. Martin Waszak
Mail Stop 132
NASA Langley Research Center
Hampton VA 23681-2199
757-864-4015
m.r.waszak@larc.nasa.gov

Dr. Leonard Wojcik
MITRE Corporation
Center for Advanced Aviation System
Development
7515 Colshire Drive
McLean VA 22102-1242
703-883-6590
lwojcik@mitre.org

APPENDIX

AVAILABLE PRESENTATION CHARTS

Network Theory: A Primer and Questions for Air Transportation System Applications

ABSTRACT

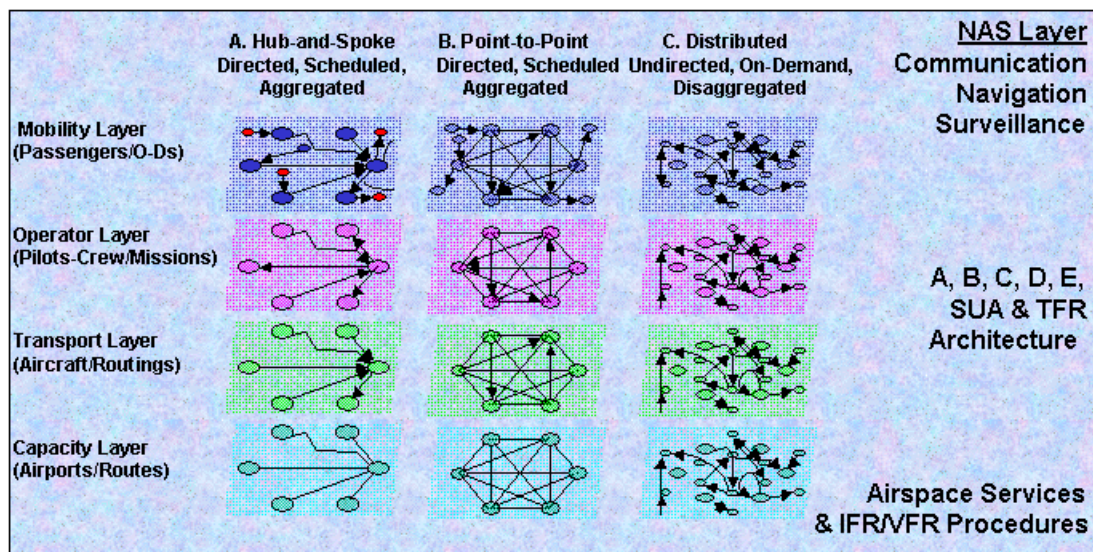
A new understanding (with potential applications to air transportation systems) has emerged in the past five years in the scientific field of networks. This development emerges in large part because we now have a new laboratory for developing theories about complex networks: The Internet. The premise of this new understanding is that most complex networks of interest, both of nature and of human contrivance, exhibit a fundamentally different behavior than thought for over two hundred years under classical graph theory. Classical theory held that networks exhibited random behavior, characterized by normal, (e.g., Gaussian or Poisson) degree distributions of the connectivity between nodes by links. The new understanding turns this idea on its head: networks of interest exhibit scale-free (or small world) degree distributions of connectivity, characterized by power law distributions. The implications of scale-free behavior for air transportation systems include the potential that some behaviors of complex system architectures might be analyzed through relatively simple approximations of local elements of the system. For air transportation applications, this presentation proposes a framework for constructing topologies (architectures) that represent the relationships between mobility, flight operations, aircraft requirements, and airspace capacity, and the related externalities in airspace procedures and architectures. The proposed architectures or topologies may serve as framework for posing comparative and combinative analyses of performance, cost, security, environmental, and related metrics.

Q: What network characteristics, topologies, and technology strategies would lead to scalable air transportation system behavior?

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Proposed Topology for Air Transportation Networks

Q: What network characteristics, topologies, and technology strategies would lead to scalable air transportation system behavior?



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Outline

“A problem well stated is half solved.”

- **Why Consider Network Theory?**
- **Research Issues**
- **“Aha’s” and Cautionary Notes**
- **Network Types**
- **Salient Analogies**
- **Scale-Free Networks (Small World Behaviors)**
- **Air Transportation Network Topologies and Lexicon**
- **Percolation, Diffusion, and Cascading and Organizational Architectures**
- **Robustness and Vulnerability**
- **Summary**
- **References**

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Research Issues (Roadmap)

- **Validation of a topology as framework for transportation networks**
- **Establishment of a lexicon for transportation networks**
- **Network modeling and simulation tools and methods**
- **Demonstration problems in network-based transportation systems and architectures**

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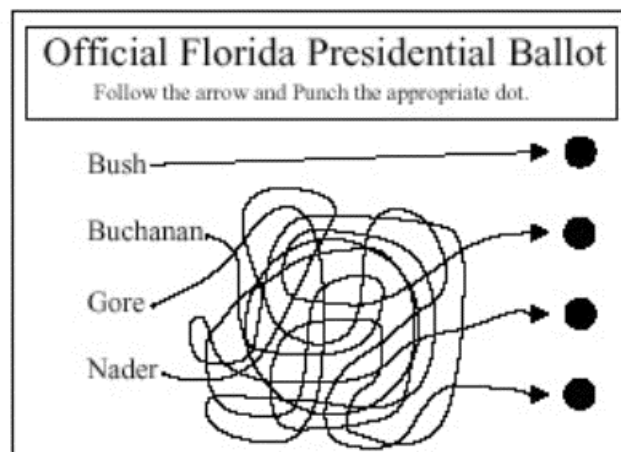
Why Consider Network Theory?

- Network theory offers a framework for system-level thinking and analyzing air transportation architectures as networks.
- Network theory provides tools for quantitative analysis of certain network behaviors (cost, performance, robustness, vulnerability).
- The theory reveals the web-like relationships and “small world” behaviors that comprise many natural and human contrived systems.
- Network theory has implications to air transportation system component technologies (airframes, flight systems, airports, airspace-CNS, infrastructure).
- The theory offers a “constructionist” *versus* “reductionist” way of thinking at the system level.

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Network Diffusion/Percolation In a Scale-Free Network

Barabasi, 2002



How did 17,000 hits on Mike Collin's Webpage occur in one day?

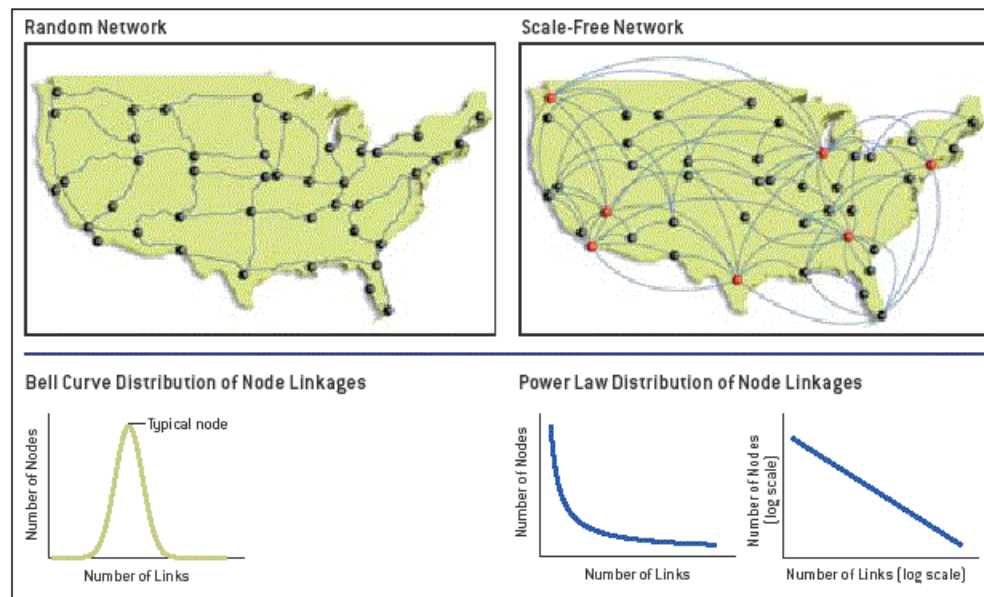
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“Aha’s”

- Air transportation topologies can serve in new ways to think about and articulate transformation, system innovation, methods and tools and scalability.
- Scalability (achievement of small-world behavior) can be a primal factor in air transportation innovation goal setting, at all layers in the topologies.
- The absence of air transportation topologies as mental models has confined much of our focus on only the infrastructure and transport layers in the architecture. The presence of a topology allows for better mental models of the linkages between mobility, operations, transport, and infrastructure layers.
- Power law distribution of nodes and links for infrastructure layer of air transportation topology can serve in new ways to think about the system layers:
 - Dis-aggregated on-demand mobility layer
 - Demand-adaptive operations/airspace layer
 - Decentralized infrastructure layer
 - Sizing of vehicles at the transport layer
- Organizational architectures must be impedance matched in order to take advantage of the diffusion properties of value webs in the delivery of products and services (i.e., technology diffusion).
- Hierarchical systems engineering processes may not address the requirements architecture and management for complexity-based systems.
- System-level outcomes are better influenced by network-based value webs where component-level outcomes are better controlled by hierarchical value webs.
- Agent-Based Modeling (ABM) is a requisite capability to handle complex network behaviors. Object Oriented technology appears to facilitate ABM system development. System Dynamics approaches (alone) will not capture complex network behaviors.

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Network Types (Barabasi & Bonabeau, Scientific American May 2003)



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Cautionary Notes

- **Modern science of networks is relatively new (~5 years in development).**
 - Leaders in the field admit, “...prospects at times appear extraordinarily exciting at times, at other times, extraordinarily hard to accomplish...”; “As tempting as it is to overstate the significance of our findings, the truth is that most of the actual science here [in network theory] comprises extremely simple representations of extremely complicated phenomena.”
- **System thinking (system of systems thinking) is a relatively young endeavor in general and in transportation specifically.**
 - Practical implementation of theory in design of transportation networks is uncharted territory (only about 7 technical papers in air transportation)
- **Any flaws in this presentation in the translation of the language of the science of networks into air transportation lexicon are the solely the responsibility of the author**
 - Corrections, ideas, and new links are welcome!

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Definitions

Network Topic	Air Transportation Translation
Aging (of nodes): Decreasing rate of attraction of new links by a node; limiting/prevention of the ability of preferential attachment to continue scale-free distribution of connectivity. All new nodes are “born” active, but may become inactive due to aging. Aging leads to cutoff of the power law decay of the tail of connectivity.	The saturation of capacity (or prohibitive cost of added capacity) in airports and airspace causes truncation of scale-free connectivity distributions (non-power law/exponential decay behavior). See <i>Small world structure/behavior</i> classes of characteristics.
Agent Based Modeling (ABM): System or network modeling based on collections of autonomous decision-making entities (agents), following prescribed rules for agent behavior and for interactions (links). ABM capable of capturing <i>emergent phenomena</i> in dynamic networks in nature.	JETWISE (MITRE Tool for scheduled airline evolutionary modeling) SWARM and 3-SWARM (freeware package for multi-agent simulation of complex systems) supported by Navy (NRL), DARPA, and Sandia TRANSIMS (transims.tsasa.lanl.gov) tool for ground traffic modeling; capable of determining <i>network reliability</i> (variability in doorstep-to-destination travel times). Agent Attributes (for supply and demand agents) –Attributes –Rules of Behavior –Memory –Sophistication –Resources

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Definitions, Continued

Network Topic	Air Transportation Translation
Aggregation (Hard and Soft)	The hub-and-spoke and point-to-point scheduled air service models operate using aggregation of travelers The scale-free on-demand service model operates using dis-aggregation of travelers. Soft aggregation is the collection of more than one traveler through options in the service business model.
Clusters/Clustering Coefficient: The probability that two classes that are neighbors of a given class are neighbors of each other; ratio of actual over possible links (e.g., the ratio of the probability that your friends know each other to the probability that two randomly selected people know each other).	The Hub-and-Spoke system exhibits strong clustering behavior (it is possible to connect between any two of the airports in the world through a very small number of links - network diameter = ~4-5); small clustering coefficient Netjets fractional ownership operations exhibit weaker clustering behavior (it is possible to connect between any two of the airports in the world with one link); Clustering coefficient approaches 1.0
Constraints: Limits on performance attributes of behavior of nodes and paths between nodes (links)	
Degree distribution: Log-log slope of links vs.nodes; constant slope for scale-free networks, non-linear slope for random networks.	

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Definitions, Continued

Network Topic	Air Transportation Translation
Degrees of Separation (d): The ratio of the logarithms of the number of nodes (N) over the number of links (k) $d = \log N / \log k$ (for a random network); $d = 0.35 + 2 \log N$ (e.g., for the scale-free World Wide Web)	
Diffusion: Process by which phenomena (innovations, infections, etc.) move through a network, from early adopters to explosive growth (global cascades), then to maturing/die-off.	Along with <i>Percolation</i> and <i>Cascading</i> , diffusion explains shaping of S-curves for innovation life cycles and transportation mode substitution/diversion behavior.
Directed Networks: Irreversible, deterministic, synchronous, scheduled behaviors and processes, e.g., chemical reactions; WWW (HTML)	e.g., in centralized or point-to-point scheduled transportation systems, transport, operation, and mobility layers are fixed, not flexible e.g., TDMA versus CDMA
Emergent phenomena: System behavior which involves non-intuitive, non-linear consequences of interactions between individual entities in a network, caused by the interactions themselves, therefore cannot be predicted by static characteristics (the whole is more than the sum of its parts; also see <i>cascading</i>)	Some debate as to appropriateness of term "emergent." Whether behavior is emergent, or merely inadequately anticipated is at issue. The term "unanticipated" behavior may be more useful for transportation systems.
Erdos Number: Degrees of separation between mathematician Paul Erdos and other mathematicians in publication citations	

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Definitions, Continued

Network Topic	Air Transportation Translation
Fitness: In a competitive network environment, fitness defines the ability of nodes to attract links (preferential attachment)	Candidate fitness metrics for air transportation nodes should be developed for all layers (mobility, operation, transport, and capacity) For air transportation, node fitness would be a product of: – Gravity Model parameters (population density, propensity to travel, distance between nodes) – Proximity of airport to trip origin and ultimate destination, with near all-weather runway capability, weather characteristics at O&D (probability of successful trip completion) – Availability of transportation service within constraints of frequency of service and cost of service (probability of successful trip initiation) – Modal choice preference factors (probability of mode choice)

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Definitions, Continued

Network Topic	Air Transportation Translation
Fitness Landscape: (Smooth; Static; Flat; ...)	In transportation, a fitness landscape would be represented by the time-dependent, geographic distribution of both gravity model distributions and runway/community air accessibility distributions. Fitness landscapes in on-demand transportation systems could display asset allocation information (aircraft, pilots, parts, limos, lunches, etc.) against demand density distributions (populations of travelers) that satisfy return on investment thresholds.
Fitness Connectivity Product: In <i>Scale-Free</i> network, the probability of connection of a new node to a node of k links is $P \sim k/\sum_i k_i$. In <i>Fitness-based</i> network, the probability is influenced by the nodes' fitness, η ; thus, the probability is $k\eta/\sum_i k_i\eta_i$.	
Graph Theory: Use of mathematical objects called <i>graphs</i> , of connections between nodes and links to developed by Leonhard Euler (1736) as the theory of random graphs	

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Definitions, Continued

Network Topic	Air Transportation Translation
Growth: In a <i>Scale-Free</i> network, rate of growth (of new nodes and new links) is proportional to the square root of time, t^{-2}; in a <i>Fitness-based</i> network, the rate at which nodes acquire links still follows a power law, t^β, where the dynamic exponent, β, measures how fast each node acquires new links. What makes modern network science truly new is the understanding that networks are <i>dynamic</i>, that networks depend on what happened previously, and that networks can be viewed as integral parts of a continuously evolving and self-constituting system. The most highly connected nodes exhibit the fastest growth (up to the limits caused by <i>aging</i>). <i>Preferential attachment</i> is a requisite characteristic of scale-free growth.	<u>Candidate Definitions:</u> Mobility Layer: •Accommodation of growing numbers of agents (travelers, packages, ...), especially in dis-aggregated transportation services Operation Layer: •Adaptation of operations and business models to varying requirements for crew (two-pilot; single-pilot; self-crewed; un-crewed) Transport Layer: •Demand adaptive accommodation of growing numbers of aircraft on short-term and long-term time scales Capacity Layer: •Accommodation of growing numbers of airports/runway ends accessible in the NAS

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Definitions, Continued

Network Topic	Air Transportation Translation
Heterogeneous Nets: Networks comprised of dissimilar elements, layers, processes. Open architectures support interoperability in <i>h. nets</i>. Such nets exhibit extremely resilient behavior under random failure, at the same time as exhibiting increased vulnerability to attack	<u>Candidate Definitions:</u> Multiple, interoperable topologies (directed, undirected, centralized, distributed, scheduled, on-demand, synchronous, asynchronous) for: ▪ Capacity Layer = Comm-Nav-Surveillance (NAS) architectures; ▪ Transport Layer = Aircraft fleet mix ▪ Operation Layer = Two-crew; single-crew; self-operated; un-inhabited ▪ Mobility Layer = Transportation service business models (scheduled, on-demand, ...); transport function (people, packages, services, ...)
Hubs (in networks): Clusters that are “fitness” derived, gaining links through <i>preferential attachment</i>	Hub and Spoke airports in scheduled airline travel Dynamically-formed higher-density airports in on-demand SATS-taxi services.
Multi-Scale Networks:	

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Definitions, Continued

Network Topic	Air Transportation Translation
Network Diameter: Degrees of Separation; increases logarithmically with the number of nodes. If 100 of my friends have each 100 friends, who in turn each have 100 friends, then I am connected to $100 \times 100 \times 100 = 1 \times 10^6$ acquaintances by four degrees of separation (four links, including myself). If each of the fourth tier of friends has 100 friends who each have 100 friends, then I am connected to $100 \times 100 \times 1 \times 10^6 = 10 \times 10^9$ acquaintances by six links (thus Six Degrees of Separation).	

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Definitions, Continued

Network Topic	Air Transportation Translation
Network Reliability: Variability in performance of network. Loss of reliability produces one source of system "waste," in a six-sigma sense.	<u>Candidate Definitions:</u> ▪ Mobility Layer: Variability in transit times from doorstep-to-destination ▪ Operation Layer: Labor dispute effects; Labor rules effects; ... ▪ Transport Layer: Delays/holds;... ▪ Capacity Layer: Weather effects; terrorism effects; ... ▪ CNS Layer: Delays in communication, navigation, and surveillance services, ... Sources of loss/lost reliability (waste) in airspace systems: ▪ Missed approaches ▪ ATC Preferred Routes (<i>versus</i> "least wind miles") ▪ Runway occupancy limits ▪ Terminal departure fix loading ▪ Radar-based separation ▪ Miles-in-trail arrival spacing ▪ Single file (no passing) ▪ Ground delays ▪ Refiling requirements

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Definitions, Continued

Network Topic	Air Transportation Translation
Nodes: Vertices in networks with characteristics of: <i>aging</i>, competition, clustering, decision-making, filtering, <i>fitness</i>, knowledge, links, cost. Nodes can be active or inactive (see <i>Aging</i>), with inactive nodes unable to gain new links.	<u>Candidate definitions:</u> Mobility Layer: • Nodes = Originations from points of departure • Links = Trips to destinations Operation Layer: • Nodes = Pilots; crew • Links = Mission profiles and labor rules/constraints Transport Layer: • Nodes = Aircraft (within the vehicle, additional topologies can be defined for structures, sensors, power distribution, controllers, computers, local networks, off-board datalinks) • Links = ATC communication; Radar surveillance; ADS-B, Airborne Internet Capacity Layer: • Nodes = Airports • Links = Jet routes, departure and arrival procedures, free-flight routes

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Definitions, Continued

Network Topic	Air Transportation Translation
Percolation (in network): An <i>emergent phenomenon</i>, the transition from independent behavior of nodes to group behavior of an entire cluster (in sociology, the formation of a community; in mathematics, the emergence of a giant component that includes a large fraction of all nodes)	
Phase Transition: Occurs when the network experiences a global cascade or transition of virtually all nodes to a new network characteristic. For example: – From liquid to solid (e.g., water to ice) – Bose-Einstein Condensate	Challenge Problem: In an on-demand, un-directed, disaggregated transportation network, what number of aircraft, serving what number of nodes, at what levels of cost and performance, will create a transition in phase as evidenced by the following system behavior shifts: – From most legs empty to most legs full – From loss to profit – From most consumers not knowing about the on-demand choice to most consumers understanding the choice

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Definitions, Continued

Network Topic	Air Transportation Translation
Power Law Distribution: Plotted as # of nodes with k links <i>versus</i> # of links (k), hyperbolic distribution for a scale-free network; contrasted with normal (e.g., Gaussian or Poisson) exponential distribution for a random network	In real-world air transportation network behavior, the capacity layer (airports and air-routing links) exhibits cutoff of the distribution of connectivity due to capacity constraints in the hub-and-spoke system. This class of <i>small-world behavior</i> is <i>broad scale or truncated</i> , exhibiting an exponential cutoff of the tail of the distribution of connectivity.
Preferential attachment (of nodes): Distance, time, cost, or other performance attributes of network behavior between nodes. Leads to formation of Hubs (See <i>Hubs</i> and <i>Fitness</i>). Gives rise to the <i>power law distribution</i> of connectivity. Preferential attachment and growth support hub-dominated, <i>scale-free</i> topologies. In a competitive network environment, <i>preferential attachment</i> is driven by the product of the node's fitness and the number of links it has (see <i>Fitness Connectivity Product</i>).	Growth by preferential attachment would be enabled through on-demand behavior of user-preferred schedule, point of origin, point of destination, and routing.

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Definitions, Continued

Network Topic	Air Transportation Translation
Re-wiring: Adaptability of <i>scale-free</i> networks illustrated by the creation of short-cuts.	Demand-adaptive system concepts for transportation services may exhibit scale-free behaviors in the mobility layer.
Robustness (related terms: reliability, vulnerability, resilience)	On-demand transportation networks will require robustness in system performance (time-of-service windows, denial-of-service rates). The robustness of an on-demand network will depend on tolerance of the network to variability in temporal and spatial dynamics of demand and of weather, equipment and crew positioning, <i>etc.</i>
Scale-Free Topology: A basic feature common to complex networks whereby a microscopic structure and a macroscopic structure appear the same; when small bits of the network are magnified, they resemble the whole. See comments on resilience under " <i>Heterogeneous Nets</i> ." Scale-free networks emerge under conditions of network <i>growth</i> with <i>preferential attachment</i> between nodes.	Demand-adaptive system concepts for comm-nav-surveillance architectures and airspace procedures may exhibit scale-free behaviors in the capacity and transport layers. Scale-free in air transportation means that a service operating schedule could be responsive in "real time" to fitness-based, preferential attachment by links between nodes; that is, trips are on-demand schedule requirements by traveler between O-Ds, not based on providers' schedules.

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Definitions, Continued

Network Topic	Air Transportation Translation
Scalability (of networks): The ability of the network to grow by preferential attachment, as enabled through nodal fitness.	Scalability by layer in a notional air transportation topology would be enabled at each layer by certain technology strategies, for example: Physical (airports) Layer: Scalability would be enabled by technologies that enable every runway end to be equally approachable in common weather conditions. Transport (aircraft) Layer: Scalability would be enabled by lower total operating cost per unit payload/speed for aircraft in fleet operations. Operations (crew, controllers) Layer: Scalability would be enabled by technologies that reduce the burden (cost, complexity) placed on the network by crew and controller requirements (e.g., single pilot or non-piloted aircraft; airspace operations with reduced controller interaction requirements). Mobility (travelers, cargo) Layer: Scalability would be enabled by user-preferred schedules (on-demand) and points of origin and destination. National Airspace System (NAS architecture, procedures, services) Layer: Scalability would be enabled by demand-adaptive technologies such as airborne-centric capabilities for separation and sequencing.

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Definitions, Continued

Network Topic	Air Transportation Translation
Small World Structure/Behavior: A basic feature common to <i>scale-free</i> networks wherein they exhibit (a) <i>clustering coefficients</i> larger than random networks, and (b) the <i>network diameter</i> (degree distribution) increases logarithmically with number of nodes. Any constraint limiting the addition of new links is a controlling factor for the emergence of <i>scale-free</i> behavior.	
Three classes of <i>small-world behavior</i> are in the literature: (1)<i>Scale-Free</i> Networks decay with power-law, (2)<i>Broad-Scale</i> Networks decay with power-law followed by a sharp cutoff, and (3)<i>Single-Scale</i> Networks decay with a fast-decaying tail/minimal power law segment.	SATS notionally exhibits a greater degree of scale-free behavior for air transportation than other modes Hub-and-Spoke notionally exhibits <i>Single-Scale</i> network behavior (Note: Is it acceptable to build composite depictions of power-law groupings for the three classes of small-world behavior?)
Topology: architecture of relationships between nodes and links; can be emergent or self-determined in scale-free networks	

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Definitions, Concluded

Network Topic	Air Transportation Translation
Undirected Networks: Reversible, non-deterministic, asynchronous behavior and processes	e.g., on-demand, distributed transportation systems; transport layer routings not fixed; mobility layer routings flexible e.g., CDMA <i>versus</i> TDMA

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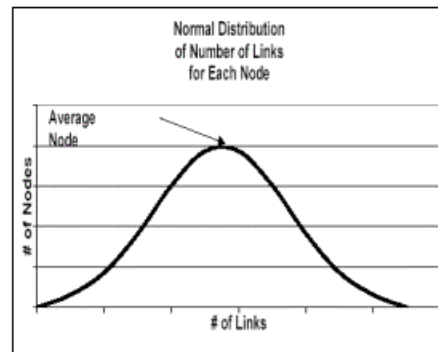
Scale-Free Networks (Small Worlds)

- **The signatures of Scale-free networks include:**
 - Small-world behavior (degrees of separation)
 - Power-law distributions of links between nodes
 - Constant clustering coefficient
- **Small world networks can be scale free to varying degrees**
- **Small world networks exhibit dynamics (network growth by preferential attachment)**

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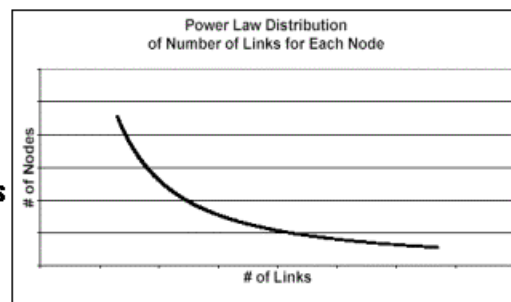
Scale Free Networks – Characteristics

- We thought that normal-type (or Poisson) probability distributions were how the degrees of distribution of # of links for each node in networks could best be modeled. This thought was based on our belief that networks were generally random, with the largest number of average nodes being highly connected and the fewer number of nodes being poorly connected.



This turns out to be incorrect.

- **Power law distributions characterize the degrees of connectedness of nodes by # of links for most all networks of interest. These networks are scale-free with most nodes being poorly connected and a few nodes being highly connected.**



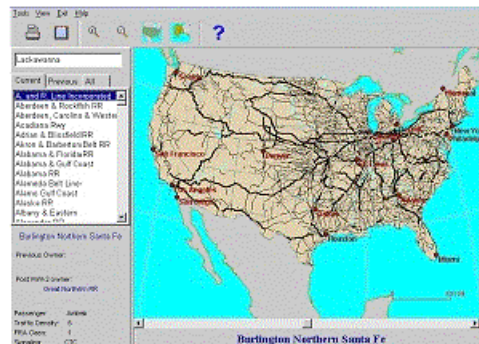
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Scale Free Networks – Characteristics

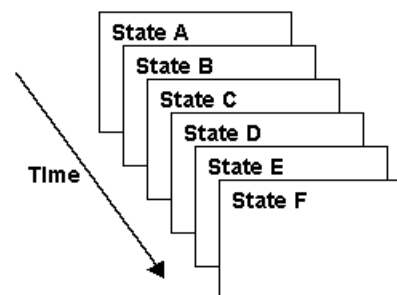
Dynamic Behavior: Evolution and Growth

- We thought that static network models were adequate to understand network behaviors.

It turns out this is incorrect.



- **Networks of interest (scale-free) evolve, grow, have time-dependence. The current state of scale-free networks depends on what went on in the network before. What follows next in a scale-free network includes preferential attachment based on the current state of the network.**



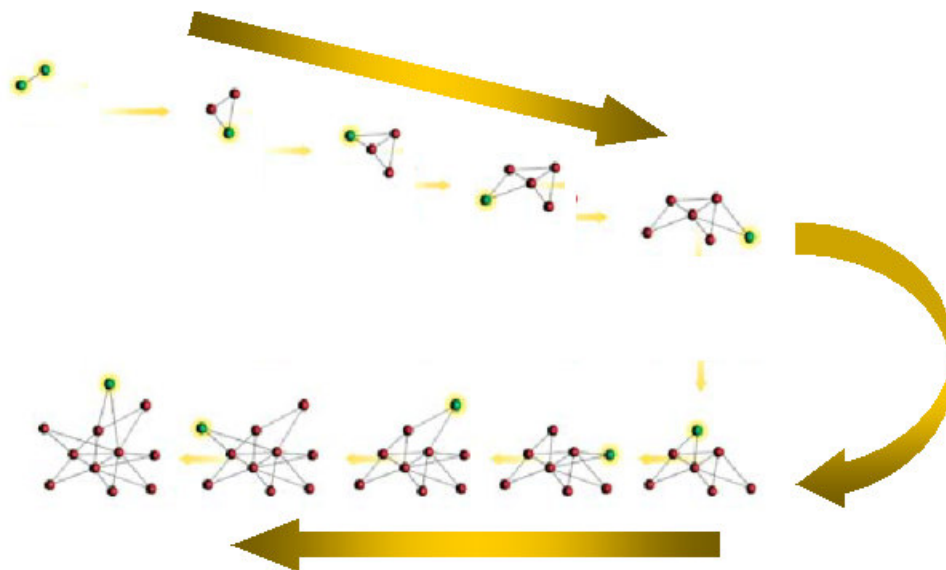
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Salient Mathematical Analogies (Network Diameter)

- **Bose-Einstein Condensate (& phase changes)**
- **Brain/neural processes (14 synapses in *C. elegans*)**
- **Biological Cellular Networks (3)**
- **Chemical reactions (rates of diffusion)**
- **Efficient Software Architectures**
- **Fads and manias (social behaviors)**
- **Food chains-webs (2)**
- **Hollywood (Kevin Bacon game)**
- **Investment bubbles**
- **Language (nodes = words; links = co-occurrences)**
- **Lexical Networks (links in word usage)**
- **Metabolism**
- **Power Grids (cascading failures)**
- **Railroads**
- **Stock Market (bubbles)**
- **Scientific Collaborations and Citations (4 to 6)**
- **World Wide Web (19)**

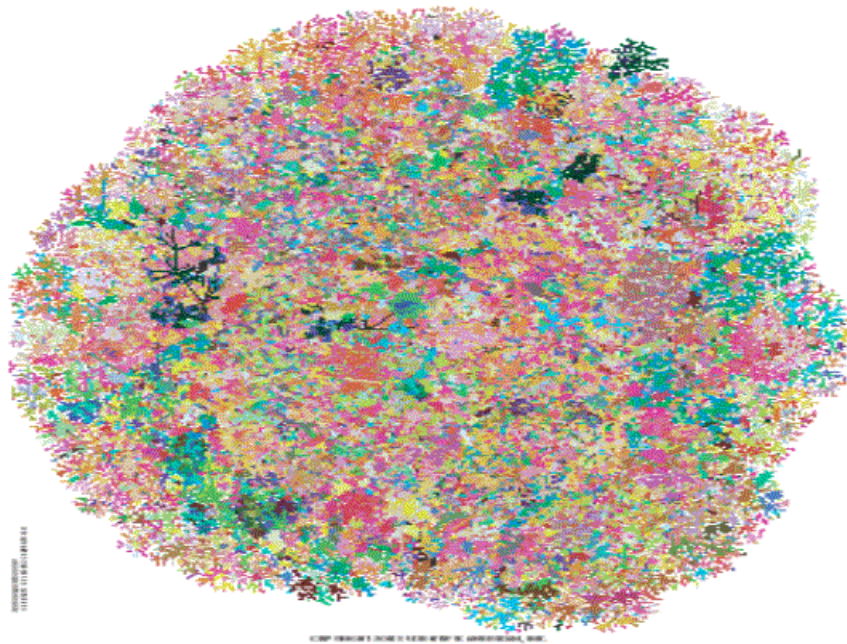
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Creation of a Scale-free Network (Barabasi)



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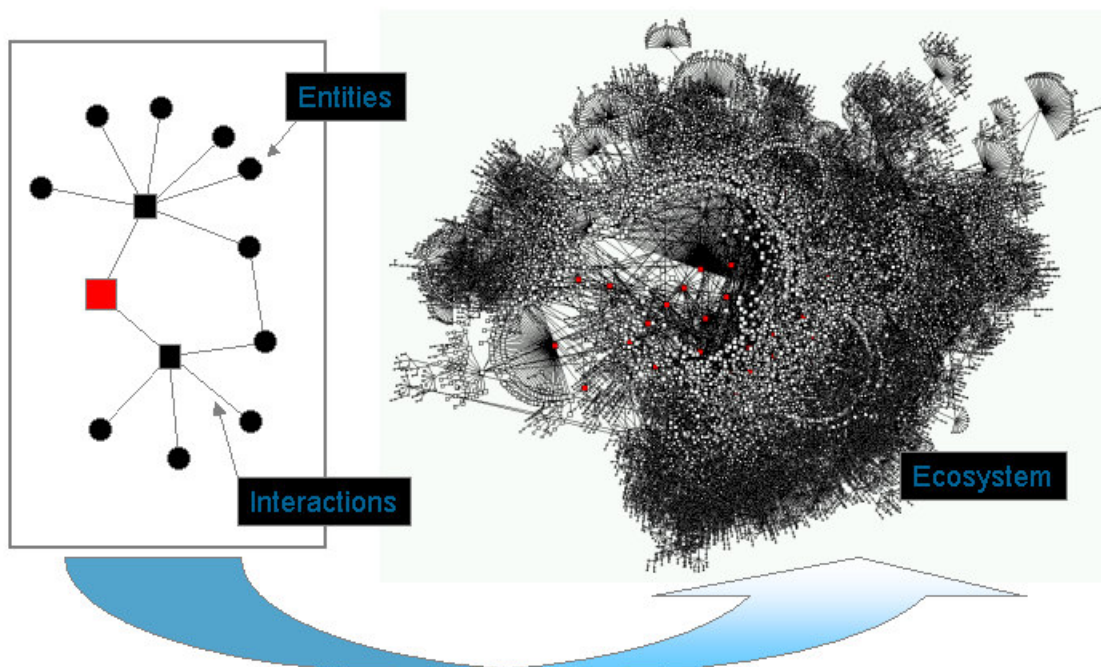
Internet Map
February 6, 2003
(Barabasi & Bonabeau, Scientific American May 2003)



Also see:
www.Peacockmaps.com
www.Cybermaps.com

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Network Definition
(IcoSystems)



Individual Actions lead to Complex Ecosystem

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Lexical Networks **(<http://visualthesaurus.com>)**

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Biological Chemistry Example of Scale-Free Behavior ***Barabasi, 2002***

***The protein-protein interaction network of yeast also has a scale-free topology:
a few proteins interact with a large number of other proteins, while most proteins have only
one or two links.***



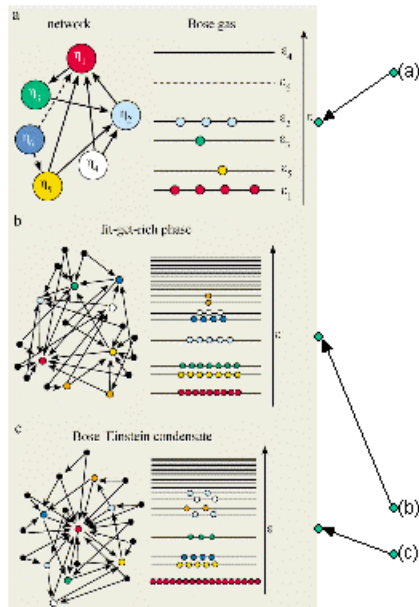
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Bose-Einstein Condensate

Example of Fitness-Based, Scale Free Network Dynamics

Barabasi, 2002

A schematic illustration of the mapping between the scale-free model with fitness and a Bose gas.



In the network each node is characterized by a randomly selected fitness, ϵ_{fit} , shown by the different colours. The **fitness** describes the node's ability to compete for links with other nodes i the fittest are more likely to acquire more links as the network grows. We assign the energy ϵ_{fit} to each node with fitness ϵ_{fit} using $\epsilon_{\text{fit}} = \exp(\epsilon_{\text{fit}})$ to obtain a **Bose gas with random energy levels**. In the mapping, the fittest nodes (high ϵ_{fit}) result in the lowest energy levels (small ϵ_{fit}). A link from node i to node j in the network corresponds to a particle in level ϵ_{fit} in the Bose gas. The network evolves over time by adding a new node (ϵ_{fit}) that connects to two other nodes (dashed lines). In the Bose gas this corresponds to the addition of a new unoccupied energy level (ϵ_{fit} , dashed), and the deposition of two new particles in ϵ_{fit} and ϵ_{fit} , the energy levels to which ϵ_{fit} connects. As the network grows, the number of energy levels and particles increase linearly in time.

The calculations show that, depending on the shape of the distribution from which the energy levels (fitnesses) are selected, two distinct phases can develop:

In the **"fit-get-rich"** phase there is no clear winner. The particle density decreases as the energy level increases.

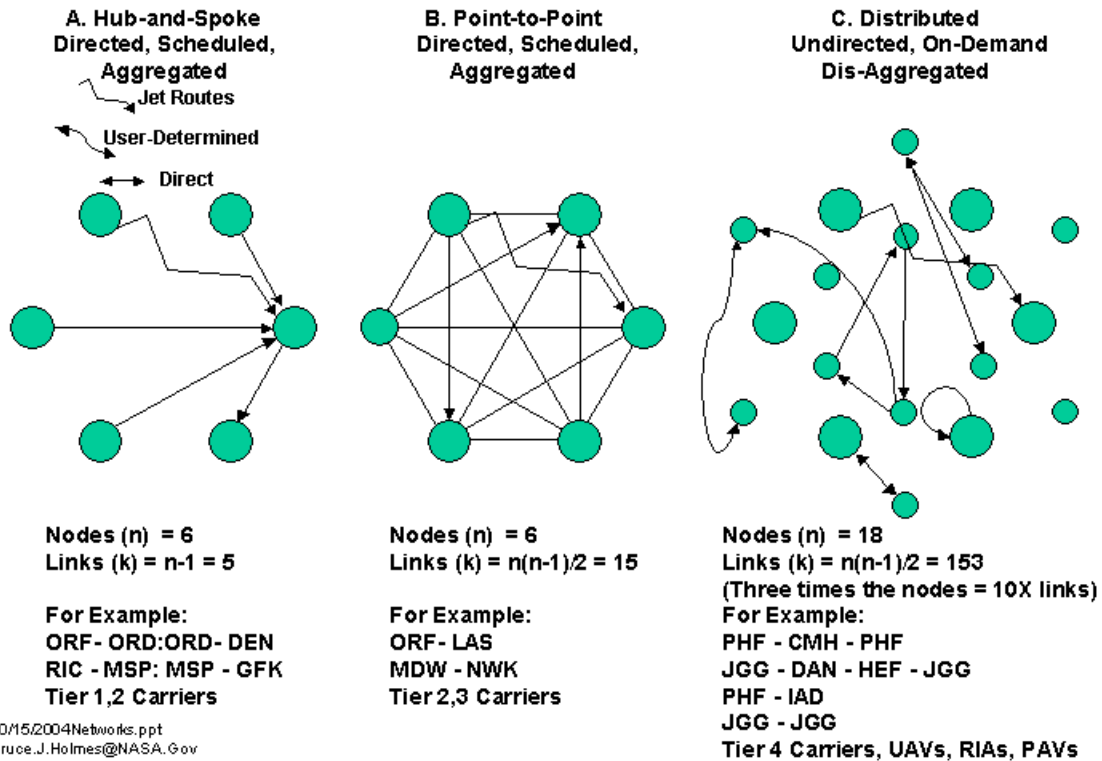
In contrast, when **Bose-Einstein condensation** takes place, the fittest node attracts a significant fraction of all links. This node appears as a highly populated, lowest energy level while higher energies remain only sparsely populated.

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Air Transportation Topologies & Lexicon (proposed)

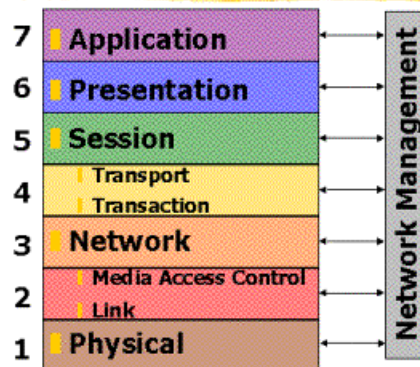
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Physical Layer for Three Air Transportation Networks



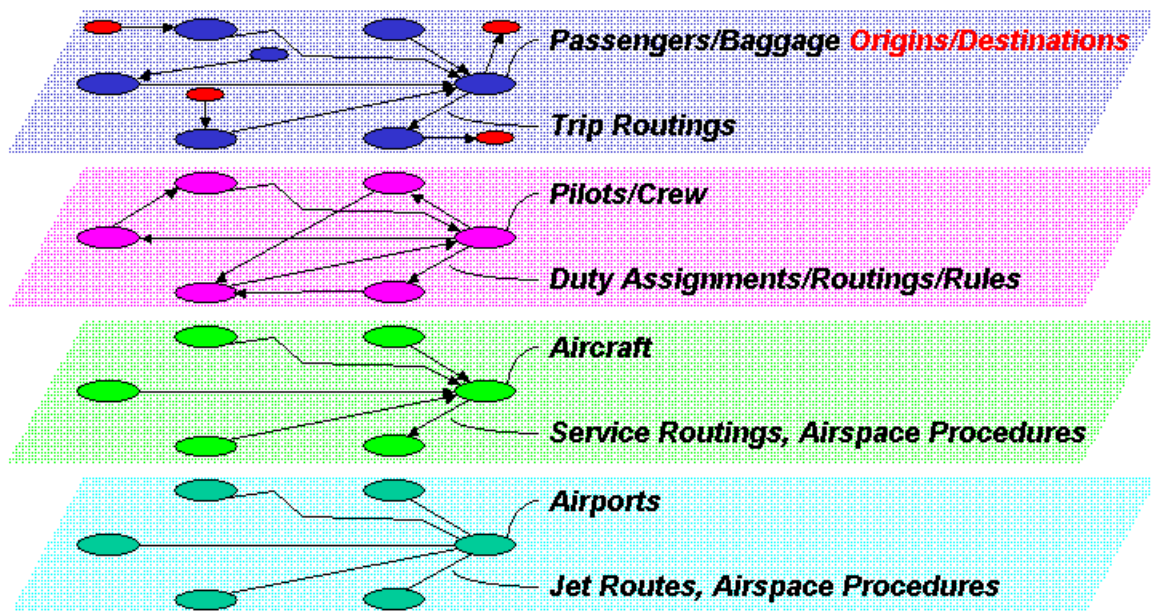
ISO (or OSI) Stack Analogy

LonTalk ISO-Model Protocol Stack



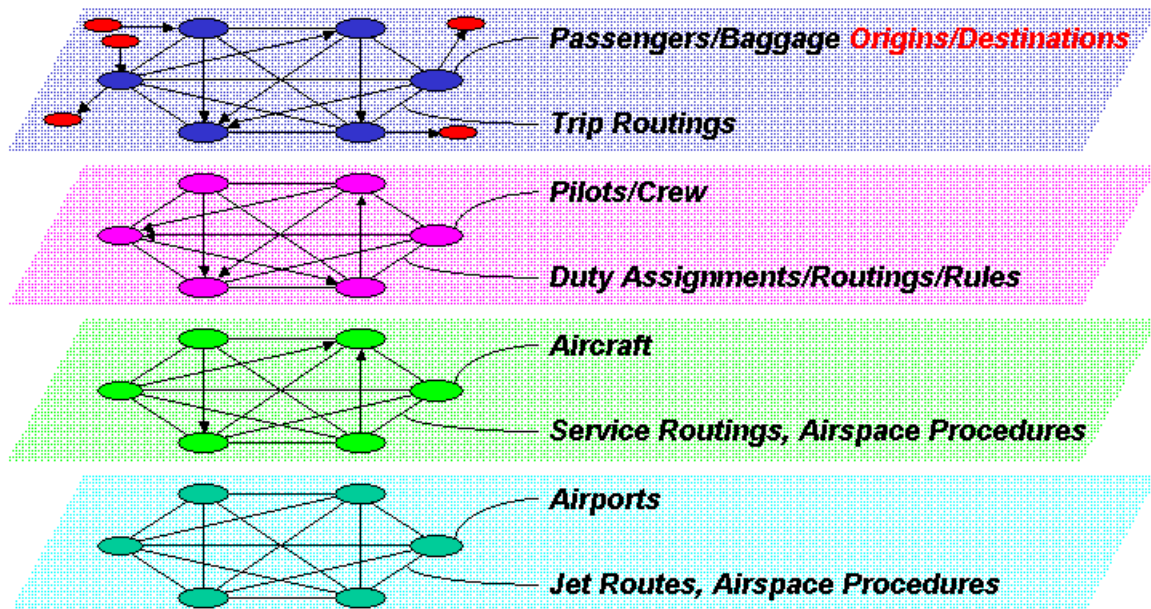
©TOSHIBA

Layered Topology in Air Transportation Network Business Stack Hub-Spoke, Directed, Scheduled, Aggregated Example



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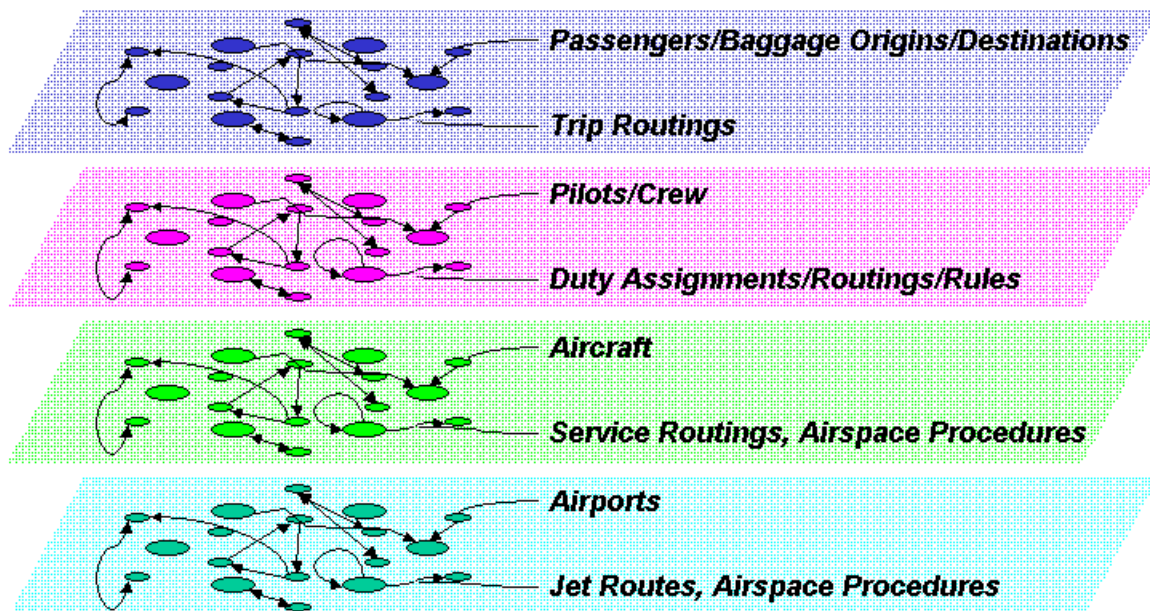
Layered Topologies in Air Transportation Network Business Stack Point-to-Point, Directed, Scheduled, Aggregated Example



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Layered Topologies in Air Transportation Network Business Stack

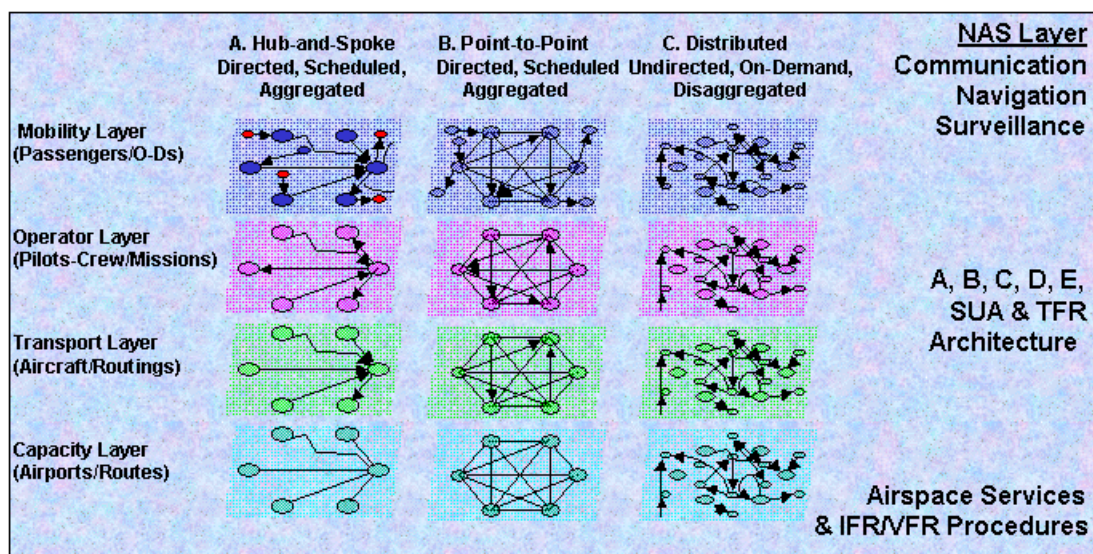
Distributed, Undirected, On-Demand, Dis-Aggregated Example



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Proposed Topology for Air Transportation Networks

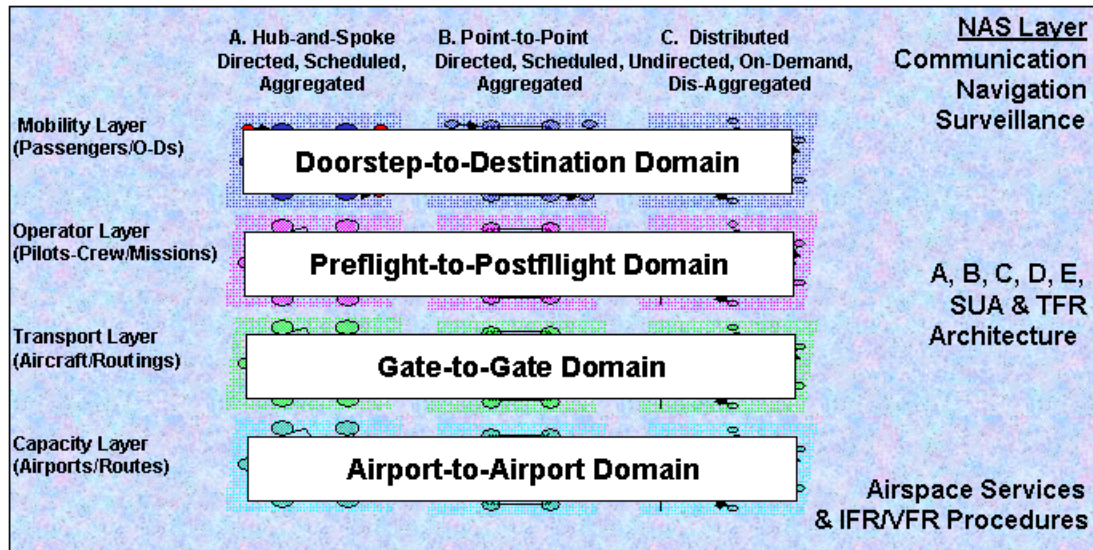
Q: What network characteristics, topologies, and technology strategies would lead to scalable air transportation system behavior?



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Domain Layers for Air Transportation Networks

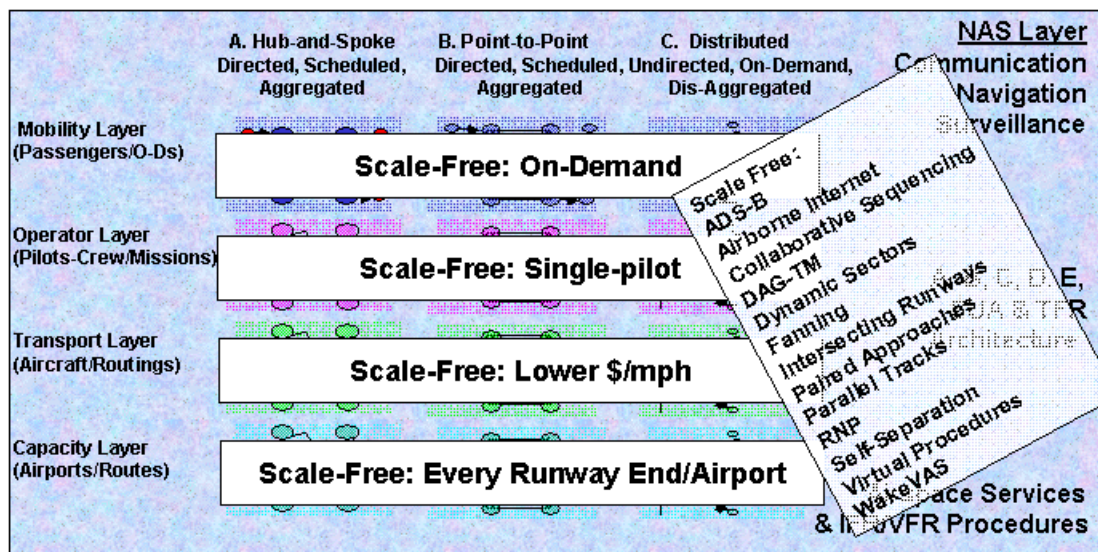
Q: What network characteristics, topologies, and technology strategies would lead to scalable air transportation system behavior?



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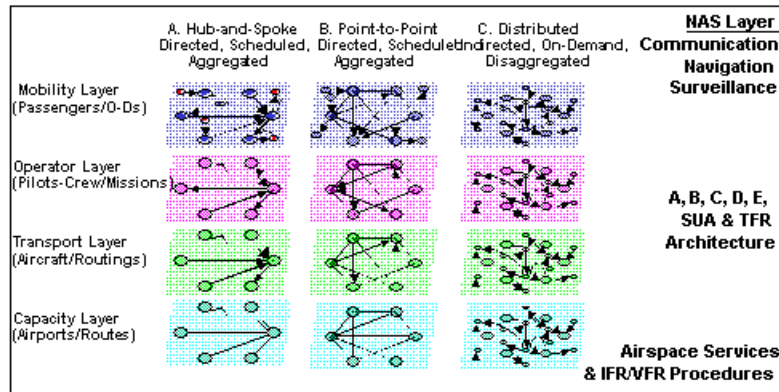
Scalability in Layers for Air Transportation Networks

Q: What network characteristics, topologies, and technology strategies would lead to scalable air transportation system behavior?



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Proposed Topology for Air Transportation Networks



Look Complex? ... IT IS!

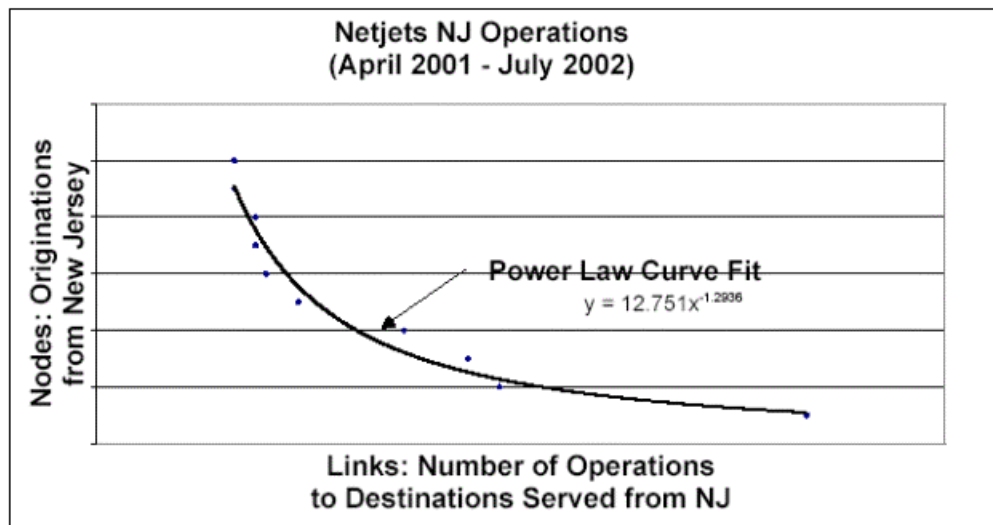
However, the implications of scale-free (or small world) theory are that understanding of global network dynamics (including self-constituting and emergent behaviors) may be approachable through simulations of simplified local elements of the network.

So, how's this different that what we do now?

Our current understandings and analytical approaches to airspace & vehicle architectures are largely based on deterministic systems (e.g., networks A and B above), and do not readily apply to non-deterministic, scale-free networks (e.g., network C above). Yet the concept of operations for a future NAS that supports distributed operations of UAV, RIA, PAV, and alternative subsonic vehicle concepts appears to require understanding of scale-free network behaviors.

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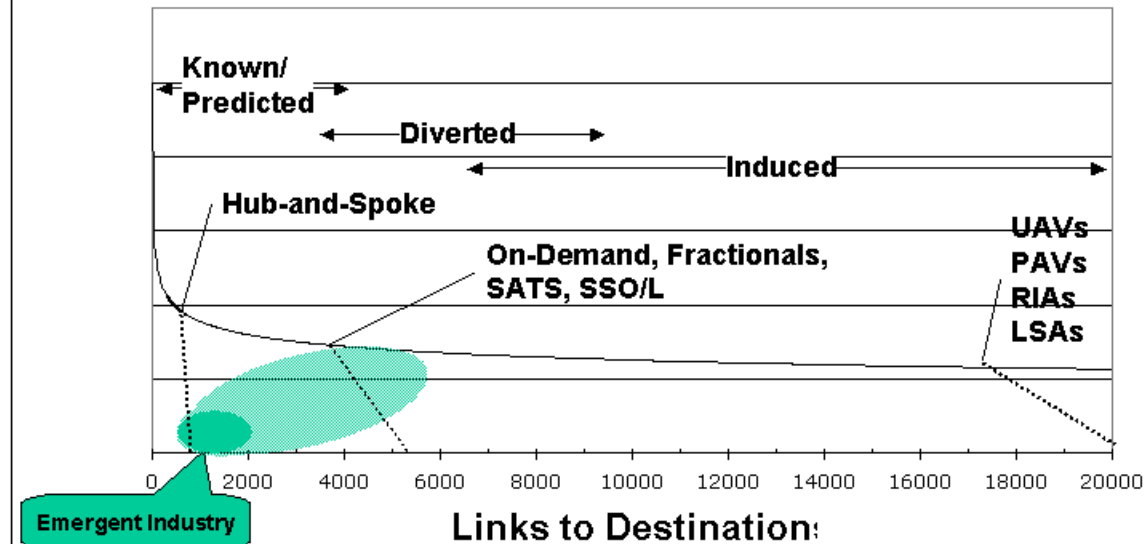
Scale-Free Distribution of NetJets Operations



- The links (operations) from a few of NetJet's nodes in NJ to their top ten destinations from NJ nodes (originations) follow a power law distribution.
- For NetJets, this distribution of nodes with links extends out to about 1250 airports annually.

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Power Law Distribution in Air Transportation (Physical & Transport Layers)

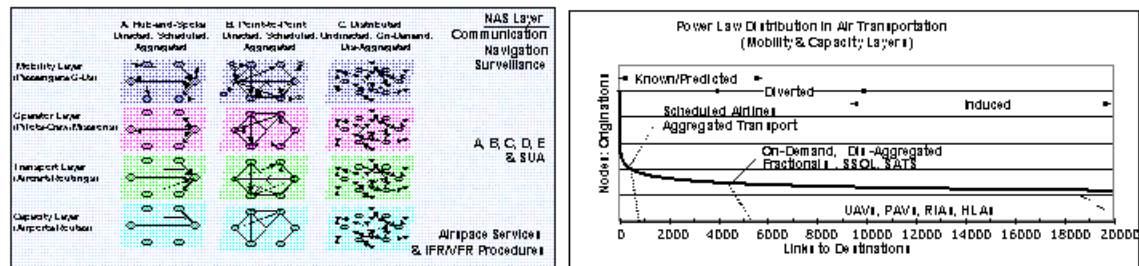


Examples of Scalable Behaviors in Air Transportation Topology

- Physical layer (airports-infrastructure) supports growing access to more runways in more weather
- Transport layer (new aircraft) supports growing access to more markets/communities
- NAS layer (airspace architecture & procedures) supports ubiquitous airspace access and services

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Air Transportation Topology As framework for primal questions

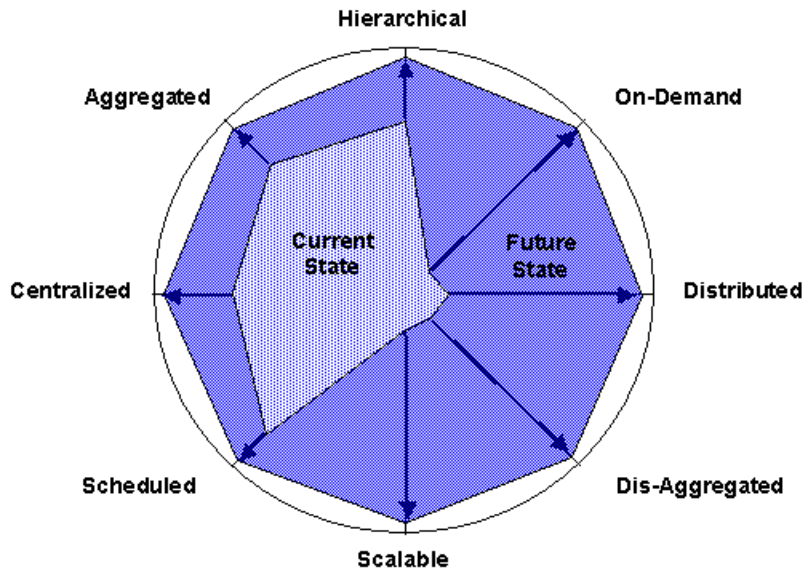


Primal Questions

1. What are the comparative mobility metrics (e.g., door-to-door speeds) for networks A, B, and C?
2. What are the optimal sizes, costs, performance of aircraft for these networks?
3. What are the comparative energy consumptions for optimized operations of these networks?
4. What are the comparative noise constraint optimization issues for these networks?
5. What are the comparative infrastructure costs at each layer of these networks?
6. What are the comparative degrees of resistance to disruptions of these networks?
7. What are the comparative degrees of vulnerabilities of these networks?
8. What are the percolation behaviors for "events" in these networks?
9. What changes occur within the network when one of the layers is fundamentally altered?
10. What topology of topologies (system of systems) expands the transformation concept space?

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Transformation Concept Space (Notional)



The vision is to expand the concept space along *all* dimensions.

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*Joint Planning Office
For the Transformation
Of The National Air Transportation System*

Percolation, Diffusion, Cascading

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Network Diffusion/Percolation

Barabasi, 2002

The spread of viruses in scale-free networks is aided by hubs-- once a hub gets a virus, it can pass it on to a very large number of nodes.

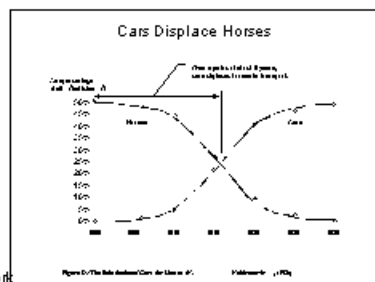
(from <http://www.orgnet.com/contagion.html>)



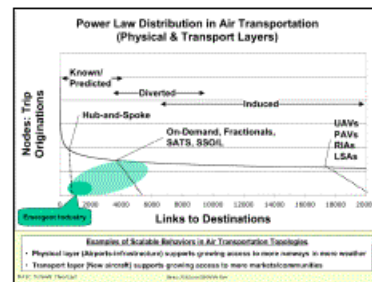
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Network Diffusion/Percolation Role in Innovation Life Cycles

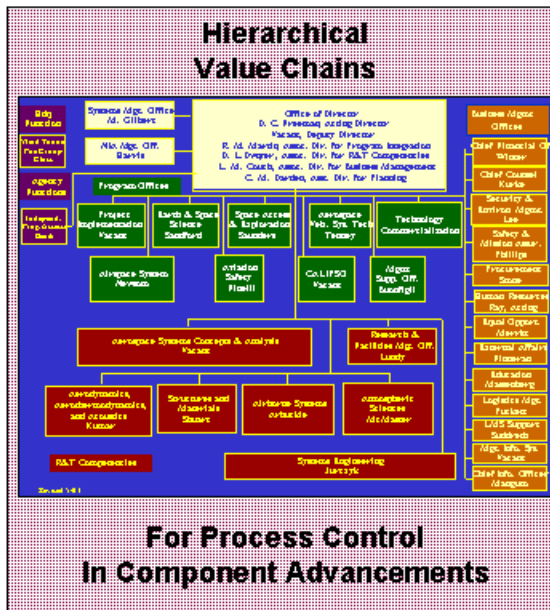
- Innovation life cycles are shaped by network behaviors
- Rates of diffusion are functions of:
 - Scale free nature of the network (growth by preferential attachment)
 - Thresholds of vulnerability (existence of need)
 - Existence of a well-connected percolating cluster (incubator for innovation)
 - Distribution of early adopters (potential for growth of links)
 - The size of the clusters of early adopters (existence of highly linked groups)
 - Links between early adopters and innovators (ability to legitimize the innovation)
- These conditions enable global cascades to occur. Global cascades exhibit self-perpetuating growth, ultimately altering the state of the entire system.



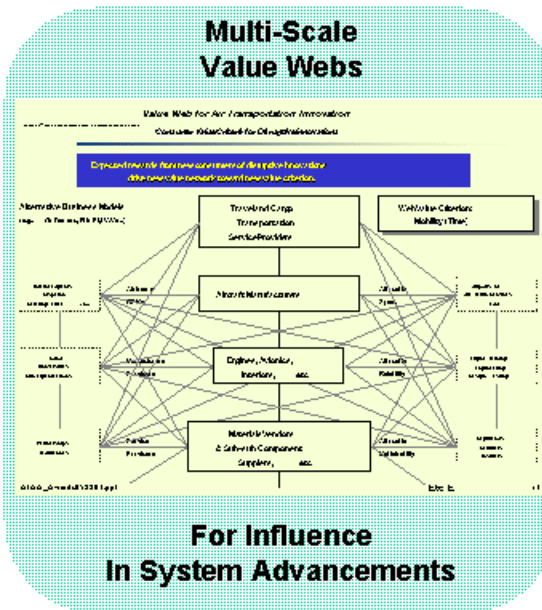
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Organizational Architectures



Hierarchical networks perform weakly in conditions of ambiguity, uncertainty, disruption.



Multi-scale networks perform strongly in conditions of ambiguity, uncertainty, disruption.

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Synergy with Object-Oriented Technology? (Is there a Nexus Here?)

- **Object Technology** appears to offer an approach to software deployment that appears highly relevant to scale-free network behaviors.
- **Object classes and subclasses** appear to have analogs within the layers of network topologies.
- **Both Object Technology and Scale-Free networks** exhibit scalability and evolution as characteristics.
- **Both Object Technology and Network Theory** have been used to understand molecular dynamics.
- **Objects** appear to exhibit node-like (network) characteristics.
- **Object Interfaces** appear to exhibit link-like (network) characteristics.

Also:

- **What is the relation between Object Technology and Agent-based modeling?**
- **What is the relation between Agent-based modeling and System Dynamics approaches?**

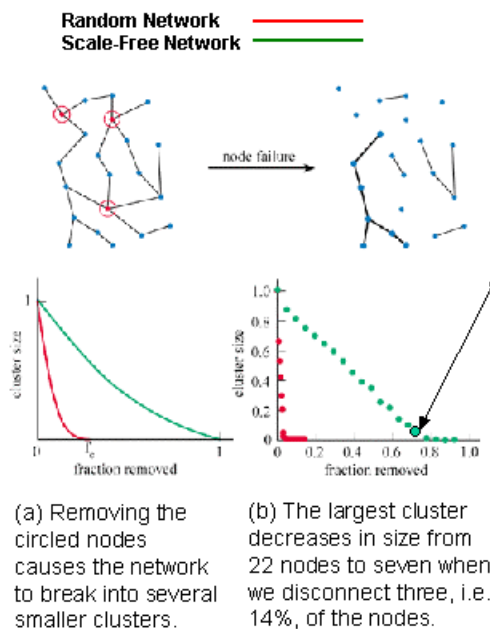
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Robustness and Vulnerability

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Robustness Analysis

Barabasi, 2002



The robustness of a complex system against errors and failures can be tested by investigating the effect of removing nodes.

(c) Percolation theory predicts that a random network will break into tiny clusters when a critical fraction, f_c , of nodes is removed. This prediction does not hold for scale-free networks as can be shown by plotting the size of the largest cluster versus the fraction of nodes removed.

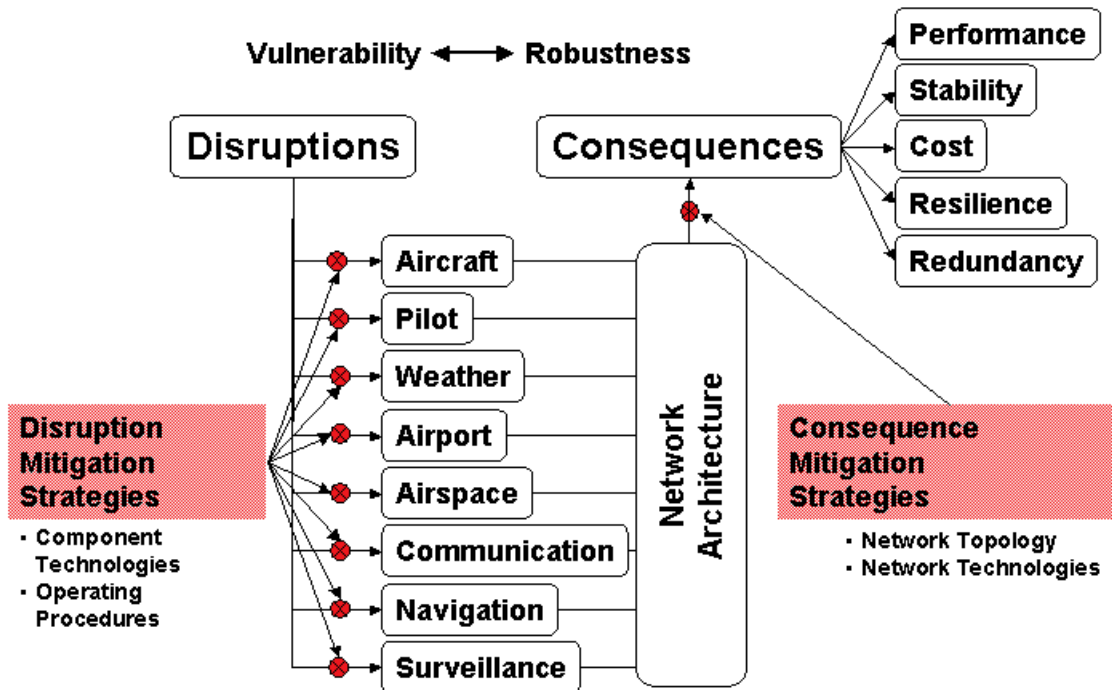
Calculations show that the cluster size only falls to zero when all the nodes have been disconnected (green). However, if the most-connected nodes are removed then the scale-free network will break at a small f_c .

(d) By randomly removing domains from the Internet, we found that more than 80% of the nodes have to fail before the network fragments (green). However, if hackers targeted the most connected nodes (red), then they could achieve the same effect by removing a small fraction of the nodes.

(from
<http://www.physicsweb.org/box/world/14/7/9/pw1407094>)

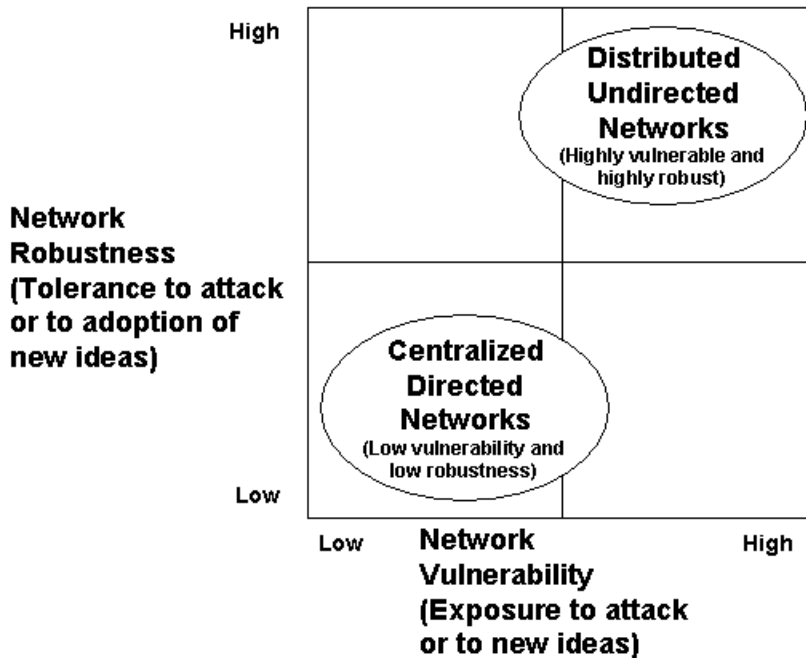
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Air Transportation System Network Architecture Effects on System Stability



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Topological Robustness



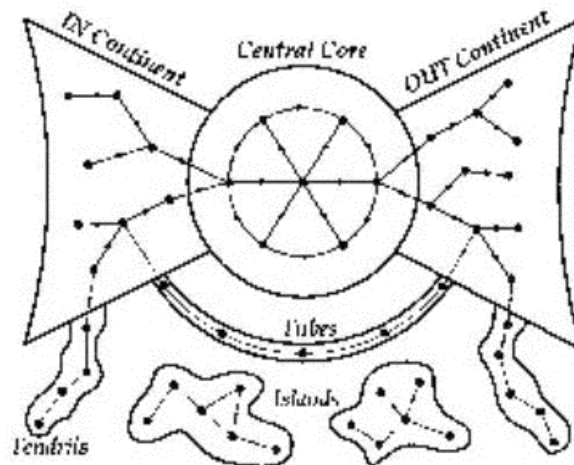
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Network Topologies

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The Continents of a Directed Networks Example of Network Non-Homogeneity

Barabasi, 2002



What is the related architecture for an Airborne Mobile Internet?

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Network Performance and Optimization Considerations

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Air Transportation Network Applications: Exploratory Questions

- What network features in air transportation system topologies lend themselves to scalability of the mobility layer? What are the tradeoffs against the other layers (capacity, transport, operation)?
- What other transportation system topologies might be appropriate for study?
 - A: Subsonic Mega-lifters: Hub-and-Regional, Directed, Scheduled
 - B: RIA: Point-to-Point, Directed Scheduled
 - C: UAV: Point-to-Point, Undirected, On-Demand
 - D: Hybrids, others?
 - E: Altered CNS, airspace architectures and procedures
- What are the implications of scale-free network performance on vehicle system technologies (distributed sensing, computing, controlling; automation; autonomy)?
- What might comprise hubbing behavior in an on-demand, point-to-point network?
- What network performance parameters would make sense for the quantification of air transportation network vulnerability, resilience, robustness, and redundancy?
- What are the implications of fitness-based, scale-free network performance on airspace architectures and technologies (Airborne Internet, Distributed Decision-making, dynamic TerPs, dynamic sectors)?
- Since all complex systems have vulnerabilities, what combinations of complex systems of individual topologies might create desired behaviors (increased robustness, performance)?
- How can an air transportation system network models be validated?

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Workshop Planning (Notional)

- **Workshop on network theory, tools, and applications in air transportation networks**
 - Purpose: Produce a roadmap between theory and applications of network theory to air transportation networks. Produce a set of problem statements, a lexicon, and assessments of readiness of tools for problem solving.
- **Participants:**
 - NASA
 - NIA
 - Academia
 - Industry
- **Outcomes:**
 - Propose lexicon for air transportation systems
 - Propose a topology
 - Determine level of readiness for computations in specific applications of the theory
 - Determine what is still at the theoretical stage
 - Identify key participants in future exploration

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Summary

- Science of networks appears to offer a framework for:
 - Ways of thinking about complex systems that could affect technology strategies, public policies, business strategies, etc. for aeronautics programs
 - Ways of analyzing simplified models of network architectures to assess alternative strategies, high level architectures, and comparative performance.
- A notional air transportation network topology is proposed
 - Lexicon: Capacity Layer; Transport Layer; Operation Layer; Mobility Layer, Disturbance Layer, CNS Layer, ...
 - Air transportation architecture assessments should include evaluation of future airspace/vehicle system architectures with properties of:
 - Scalability/Demand adaptability in numbers of aircraft operations (separation and sequencing), unconstrained by existing CNS architecture and ATC procedures
 - Negotiated-determinism (un-directedness) in origin and destination landing facilities, independent of existing airport and airway infrastructure (including jet routes, ILS, etc.)
 - Dynamic network behavior in transportation services operating models, including hubbing and non-hubbing and scheduled and on-demand systems
 - Others...
- Next steps:
 - Establish a shared lexicon
 - Identify architecture of tools and competencies for transportation network modeling
 - Establish challenge problems
 - Build a roadmap

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Sources, References, and Links

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6. Bonabeau, E.; Dorigo, M.; and Theraulaz, G.: Inspiration for Optimization from Social Insect Behavior. Progress, (Year?)
7. Buchanan, Mark: Nexus, Small Worlds and the Groundbreaking Science of Networks, Norton, New York, 2002.
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9. Rex K. Kincaid: Scale-free Graphs for General Aviation Flight Schedules, Department of Mathematics, The College of William and Mary, July 28, 2003.
10. Lederer, P.J. and R.S. Nambimadom, "Airline Network Design," Operations Research, 46 (1998) 785-804.
11. Mark Newman, Santa Fe Institute
12. Steve Strogatz: Sync.
13. S. Valverde (1) , R. Ferrer Cancho (1) and R. V. Sol: Scale-free Networks from Optimal Design ¶ e (1;2)
(1) ICREA-Complex Systems Lab, IMIM-UPF, Dr Aiguader 80, Barcelona 08003, SPAIN
(2) Santa Fe Institute, 1399 Hyde Park Road, New Mexico 87501, USA.
14. Yang, Lee; and Kornfeld, Richard: Examination of the Hub-and-Spoke Network: A Case Example Using Overnight Package Delivery. AIAA Paper 2003-1334, January 2003.
15. Watts, Duncan J.: Six Degrees - The Science of a Connected Age. W.W. Norton Co., NY, 2003

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“Let’s Get Connected”

Some Ideas and On-going Research

Dan DeLaurentis

*School of Aerospace Engineering at Georgia Tech
for
NIA Transportation Network Topologies Workshop*

DeLaurentis, Georgia Tech

12/9/03

Chaos-to-Order . . . Almost!

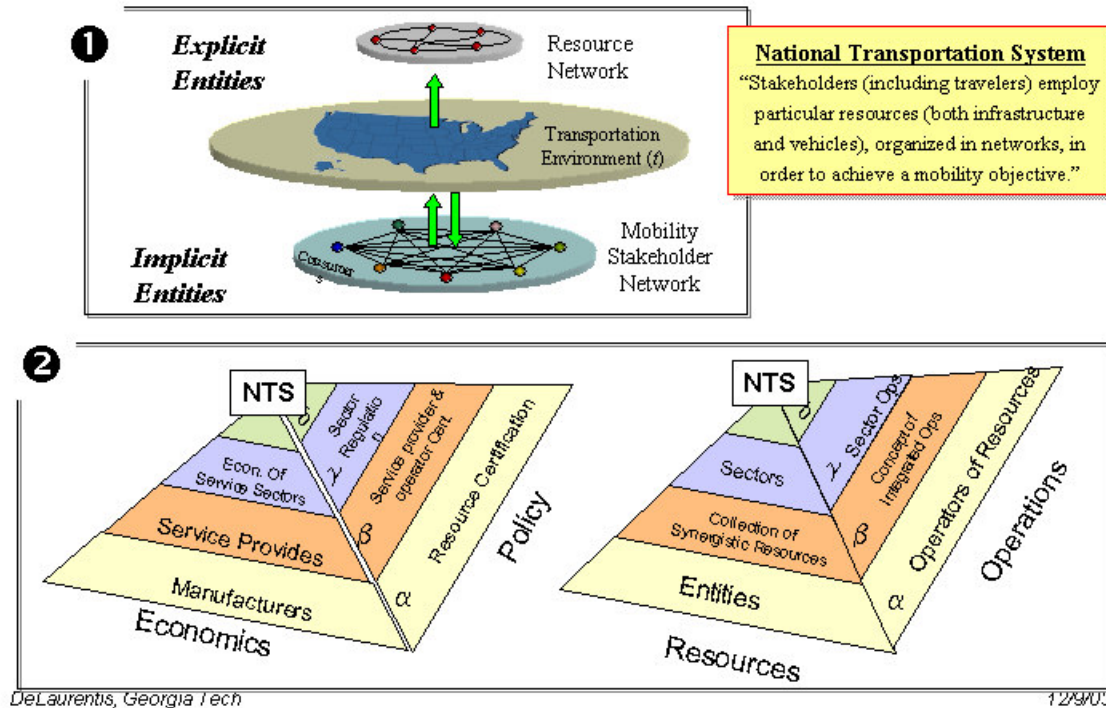
Some history with Network Theory

- Through ONR Grant, we were invited to attend Sante Fe “Summer School” for Complex Systems (Prof. Mavris & myself, a “fresh” Ph.D.)
 - There, we were also exposed to one of the leading thinkers in biological/evolutionary networks, Dr. Stuart Kauffman
 - Together with some resident researchers, we became excited about evolutionary analogies for studying “fitness” of complex systems through technology selection (“n-k landscape”)
- Encountered two major problems:
 - Lexicon, Lexicon !
 - Our case was not random! Technologies had compatibility constraints, preferred connections, not randomly generated fitness landscape. Network models at that time failed to handle this.

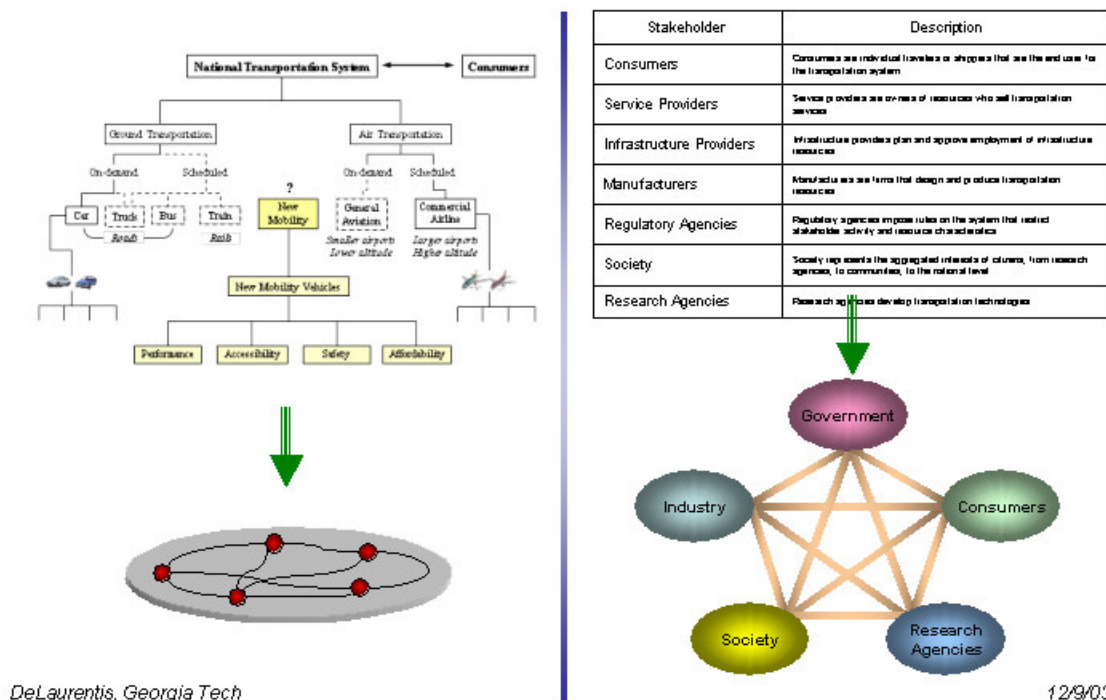
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About Lexicon- Abstraction before Analysis



They're Linked: Entity Networks



Some Distinguishing Characteristics

Network Models for Transportation

- Nodal characteristics are important
 - This is understood in network theory through, for example, the fitness concept
 - But, the throughput at nodes in accepting the “link device” (e.g. aircraft) is important to determine efficiency
- “Links” in transportation are unique
 - The resource (vehicle) used to complete the link determines the speed of travel and/or which nodes can be visited
 - Nodes have fitness (their ability to attract links), but so do links?
 - Can we account for this ?
- How do we handle “physical” and “non-physical” networks *together* (business models with aircraft . . . Bruce’s layered topologies)

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Economic-Policy Guidance

The “Big” Question

- Can we use network theory, in concert with other methods, to derive near term investment and policy decisions that are robust over an ensemble of plausible transportation futures?
 - Organizations like JPO would like to know
- Reflect on guidance from recent RAND report on Long-Term Policy Analysis (LTPA)
 - Establish ensemble of plausible scenarios
 - Identify robust strategies that **adapt**
 - Test hypotheses through scenario simulations
 - Look at time evolution of strategies...not snapshots

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The Object Oriented : Network Marriage

- Proper abstraction leads to:
 - Greater understanding of function & structure
 - Increased possibility for innovative thinking
 - Clear emergence of object-oriented methods for effective, collaborative computer simulation
- Demonstration: UAV-based package delivery network
 - Resources, economic stakeholders, and networks treated as distinct classes, prescribed with a list of attributes which can easily be manipulated for each (or during each) simulation
 - Number of nodes, placement of new nodes, rate of node dissolution, rules for links, etc. can be easily manipulated
 - ABM + OO + Computers !

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Example- UAV Package Delivery Architecture

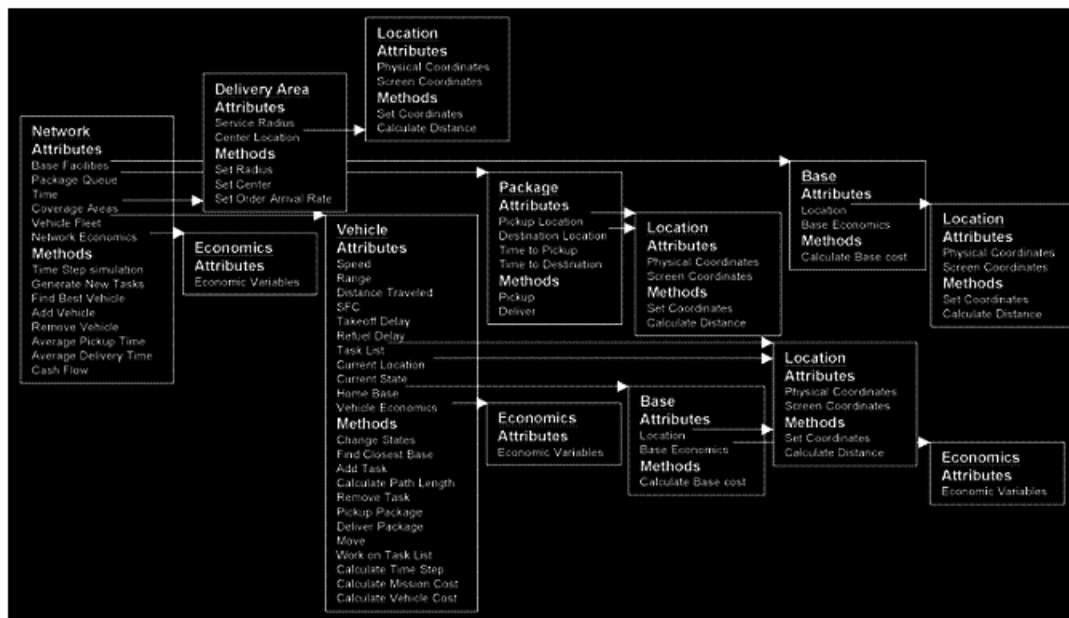
Scope and Diversity of Solution Space is Extreme

Horizontal Delivery System Topology	Hub & Spoke	Point to Point	Hybrid Distributed	Dynamic Network Topology	
Strategic Control (Dispatch)	Centralized	Distributed to Hubs	Distributed to Vehicle		
Package Type	Document	Standard Mail	Small Parcel (< 50lbs, < 2x2x2 ft)	Freight (sizes above Small Parcel)	
Service radius	Urban (< 50 miles)	Regional (50 - 500 miles)	National (> 500 miles)	International	
Shipment Time	Same-day (SuperExpress)	Next-Day (Express)	Same-week	Variety	
Vehicle Type	Fixed Wing A/C (wide-body Jet or regional turboprop)	Trucks and Vans	Autonomous VTOL- Heavy	Autonomous VTOL- Light	Small Mobile Vehicles (Bicycles, etc)
Air Traffic Control	Current ATC	ADS-B	ADS-B (TIS-B, FIS-B)	VTOL Corridors	Free-Flight
Operation Control	Autonomous	Semi-Autonomous	Non-Autonomous (Slave)		
Package Sorting	Current System	Sort at each stop/hub			
Package Tracking	No tracking	Update Tracking at each stop	GPS Tracking / per vehicle (real time)	GPS Tracking / per package (real time)	Hand tagging
Number of Hand-offs	Two (Pickup/Delivery)	Three (pickup, transfer, delivery)	Four	Five	Six
Pick-Up/Delivery Approach	Fixed number of standard "smart" containers	Customer packaging, restricted in size & volume			
Terminal Routing Delivery	Standard Grid System	Unconstrained, Real-time optimized delivery plan	Constrained for high air traffic density areas	Constrained for high ground traffic density areas	
Movement of Information ¹	Limited info about delivery network states	Info passed through Central Info Processing Unit	Info passed on from point of departure to subsequent stops		

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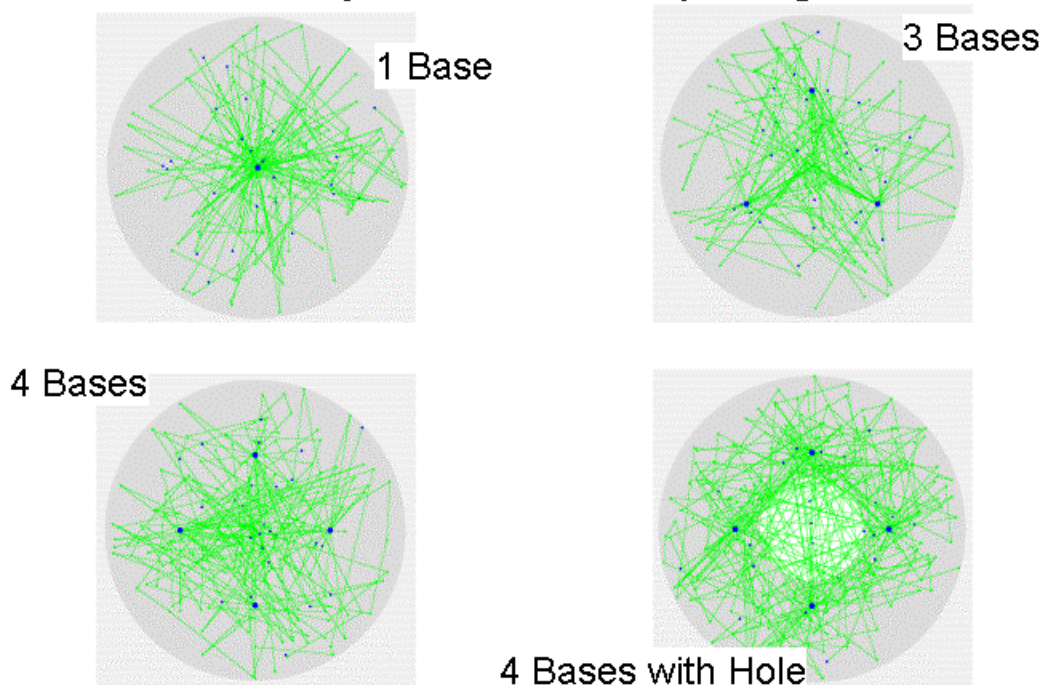
UAV Package Delivery- Object Structure



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Delivery Network Topologies



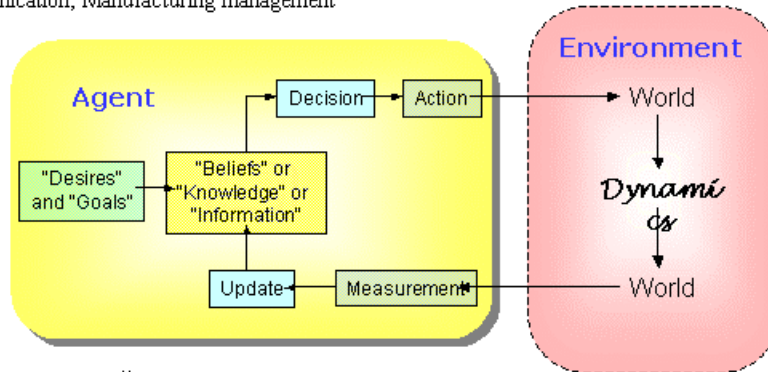
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Agent Based Modeling / Simulation

- Instead of prescribing the behavior dynamics, in ABM, individual agents (guided by rules of behavior) interact within an environment and overall system effects are observed
- A wide range of emerging applications:

Ecology, Zoology, Botany, Entomology, Chemistry, Economics, Political Science, Sociology, Psychology, Software engineering, Transportation engineering, Computer graphics, Animation, War game simulation, Communication, Manufacturing management



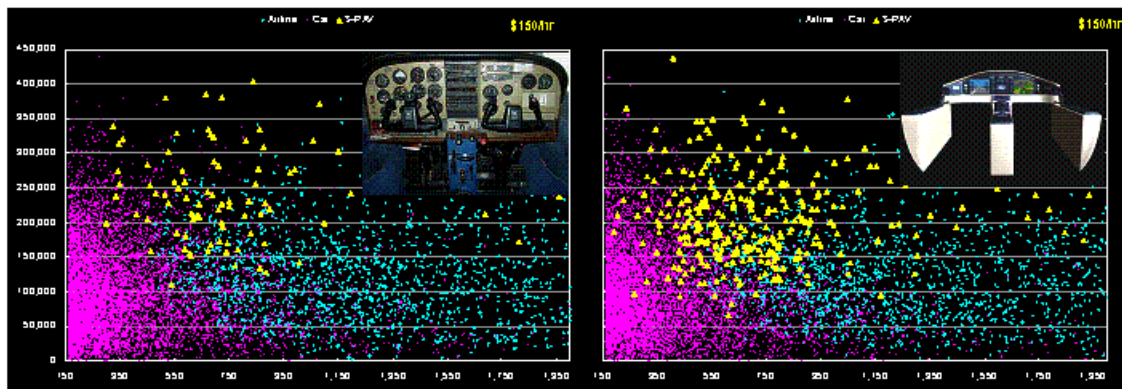
Observe **emergent behavior** from agent-environment interactions

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Effect of a SATS System Technology

- Importance of "ease of flight" ?
 - In 2000, only 0.25% of travelers didn't need to hire a pilot (the baseline assumes 50%)



X-axis: One way trip distance (km)
Y-axis: Annual Household Income (chained 2000 USD)

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What else is happening?

- What does “network theory” include?
 - “Network Centric Warfare”
 - Abstraction: “Every entity is a sensor, calling networked shooters”
 - Information sharing to multiply power
 - ISR Networks
 - Biological / Evolutionary analogies
 - Communications

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Power Laws: Some Thoughts

- Growth and preferential attachment
 - Produce Hubs
 - PAV/SATS w/o Hubs would be random network, or perhaps clusters
- Scale-free refers to Power Law behavior, not particular regions of a power law curve
- Deal with robustness – vulnerability tradeoff through “design”

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Recent, Relevant Publications

- DeLaurentis, D.A., Kang, T., Lim, S., "Solution Space Modeling and Characterization for Conceptual Air Vehicles," *accepted* for publication to *AIAA Journal of Aircraft*, to appear Jan-Feb, 2004 issue.
- DeLaurentis, D.A., Lewe, J.H., Schrage, D.P., "Abstraction and Modeling Hypothesis for Future Transportation Architectures," Proceedings of the AIAA/ICAS International Air & Space Symposium and Exhibition (Centennial of Flight), Dayton, OH, July 14-17, 2003. AIAA-2003-2514. (Invited Paper)
- Pfaender, H., DeLaurentis, D., Mavris, D., "An Object-Oriented Approach for Conceptual Design Exploration of UAV-based System-of-Systems," Proceedings of 3rd AIAA Unmanned Unlimited Conference, San Diego, CA, Sept. 15-18, 2003. AIAA 2003-6521.

Network Design:
The Example of Airlines

Professor Phillip J. Lederer

*William E. Simon Graduate School
Of Business Administration
University of Rochester*

NASA Workshop
Williamsburg VA
December 2003

There Have Been Dramatic Changes In Airline Routing Since Deregulation

I Study How Airline Economics Affects Airline Network Design

Relevance of This Strategic Issue:

Cost Pressure On Majors Due To Increasing Losses

Consolidation of Hubs

New Popularity of Direct Services

Success of Southwest Airlines

Start Up Carriers

We Study Airline Network Using An Analytic Model

Network Choice

= Routing Pattern &
Schedule (Frequency and Time To Buffer Schedule)

Consumer Choice

Service Levels To Customers

Travel Time
Schedule Delay
Late Arrival

Airline Cost and Profits

Consumer Choice

We Assume A Utility Function for Passengers
Separable In Money:

$$U = \text{Price} + \alpha \text{Travel Time} + \beta \text{Schedule Delay}$$

(Morrison and Winston Empirically Estimated
Passenger Utility Functions For This Model)

Holding U, Fixed, Choose

$$P = U - \alpha \text{Travel Time} - \beta \text{Schedule Delay}$$

ThenTraffic, D, Will Be Fixed.

Airline Profit Summed Over All Markets m :

$$= \sum (U_m - \alpha \text{Travel Time}_m - \beta \text{Schedule Delay}) D_m - \text{Operating Cost} - \text{Fixed Cost}$$

Where

Operating Cost-Fuel, Crewing, Maintenance

Fixed Cost-Aircraft Capacity and Mix

Thus, Maximizing the Firm's Profit By Choosing Network,
Schedule and Prices

Is Equivalent To

Minimizing The Sum of Airline and Passengers' Cost By
Choosing Network Design Subject to Meeting Fixed Demand

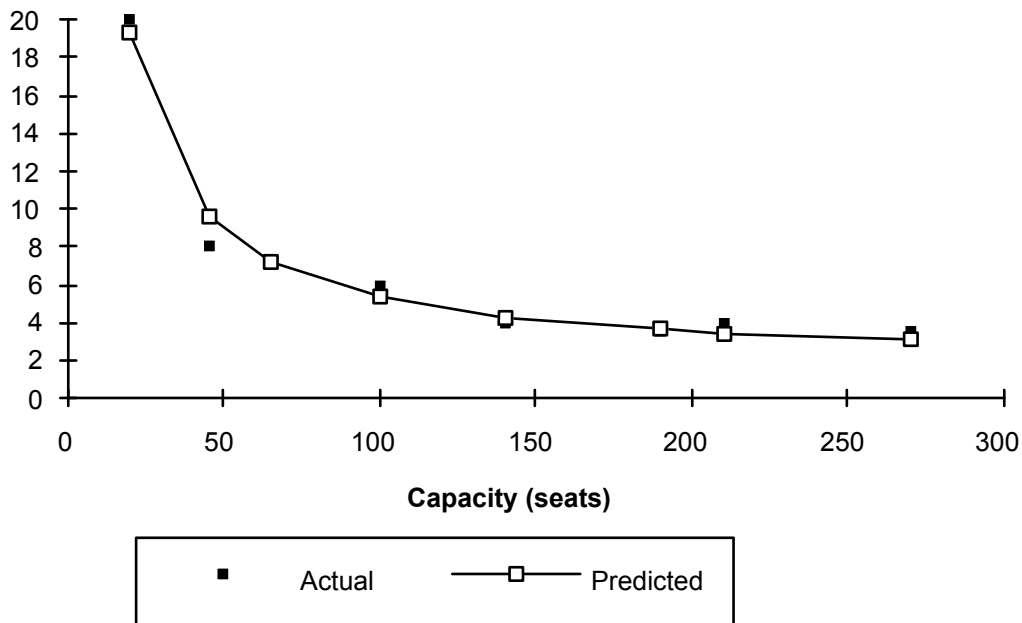
This Is A Necessary, But Not Sufficient Condition For Profit
Maximization

Airline Costs:

Empirical Data Obtained From Major Carrier

Operating Costs: Display Economies of Scale

Actual vs. Predicted Variable Cost/ASM



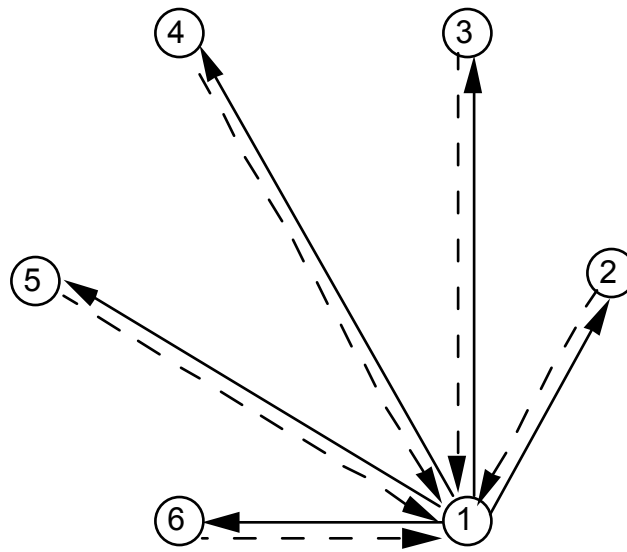
Variable Cost Per Available Seat Mile (ASM): Actual and Predicted.

$$\text{Predicted Model Cost/ASM} = 1.79 + 351.93 \frac{1}{\text{Seats}} ; R^2 = .98$$

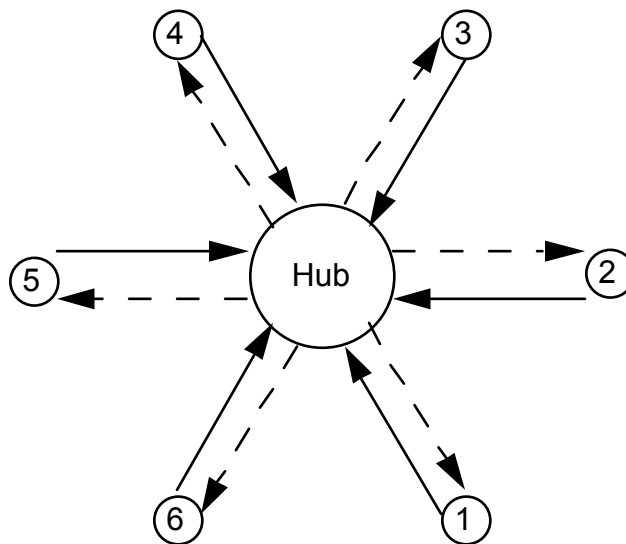
(4.3) (17.6)

(Number in parentheses are t-statistics)

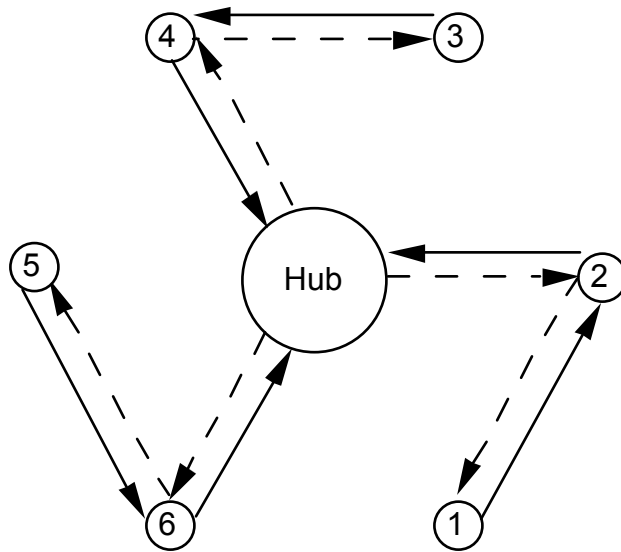
Routing Patterns



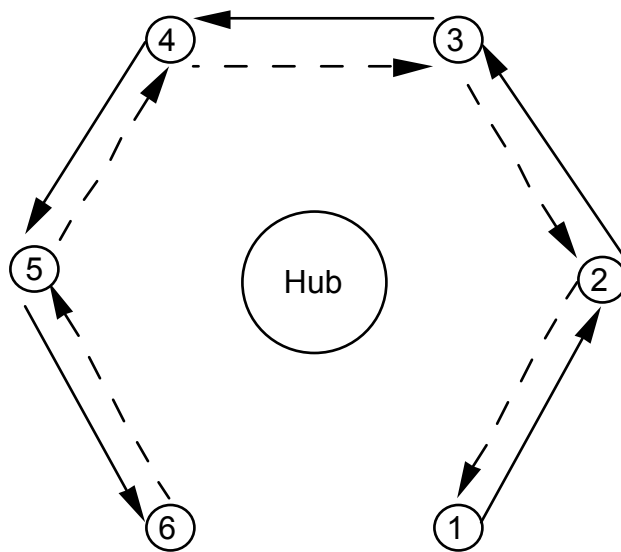
Direct ($k=0$)



Hub and Spoke ($k=1$)



Subtour ($1 < k < n$, in this example $k = 2$, $n = 6$)



Tour ($k = n$; in this example $n = 6$)

Passenger Costs

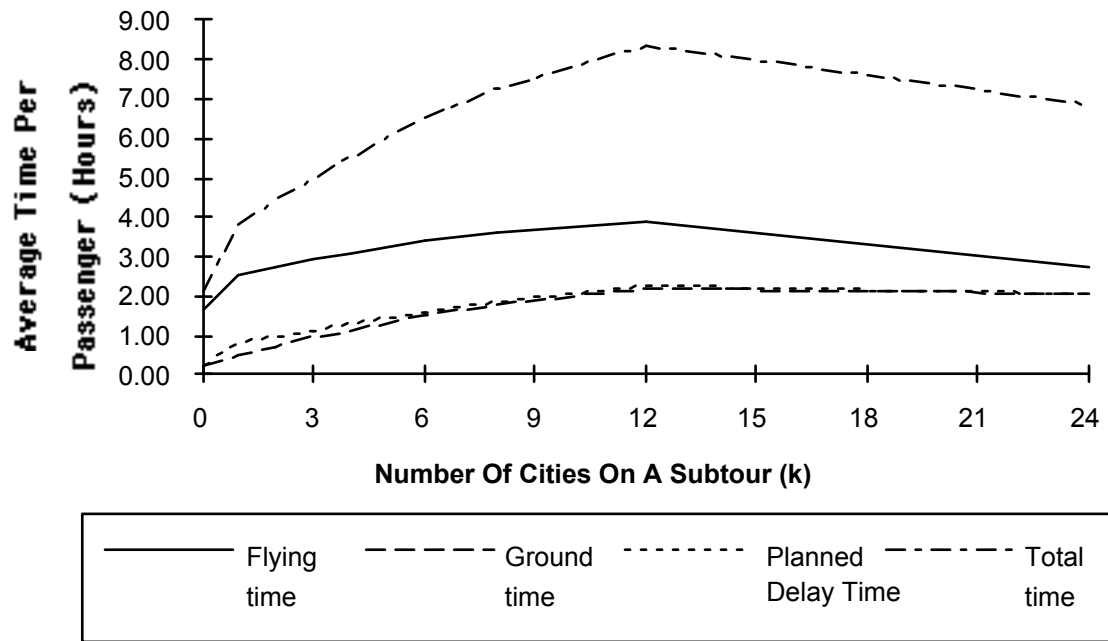
- Schedule Delay,
- Real Delay and
- Travel Time

Travel Time=

- Boarding
 - Takeoff
 - Delay Time At Takeoff
 - Flying time
 - Delay Time At Landing
 - Landing
 - Disembarkation
- Ground Time
- Ground Time

Summing The Passenger Travel Time:

**Average Travelling Times Per Passenger Vs.
Number Of Cities On A Subtour**



Parameters: $R = 500$ miles, $\rho = 25$ passengers/day,
 $v = 400$ miles per hour, $g = .25$ hours, $\alpha = .8$, $\lambda = 12$,
 $f = 12$ dispatches, and $n = 24$ cities.

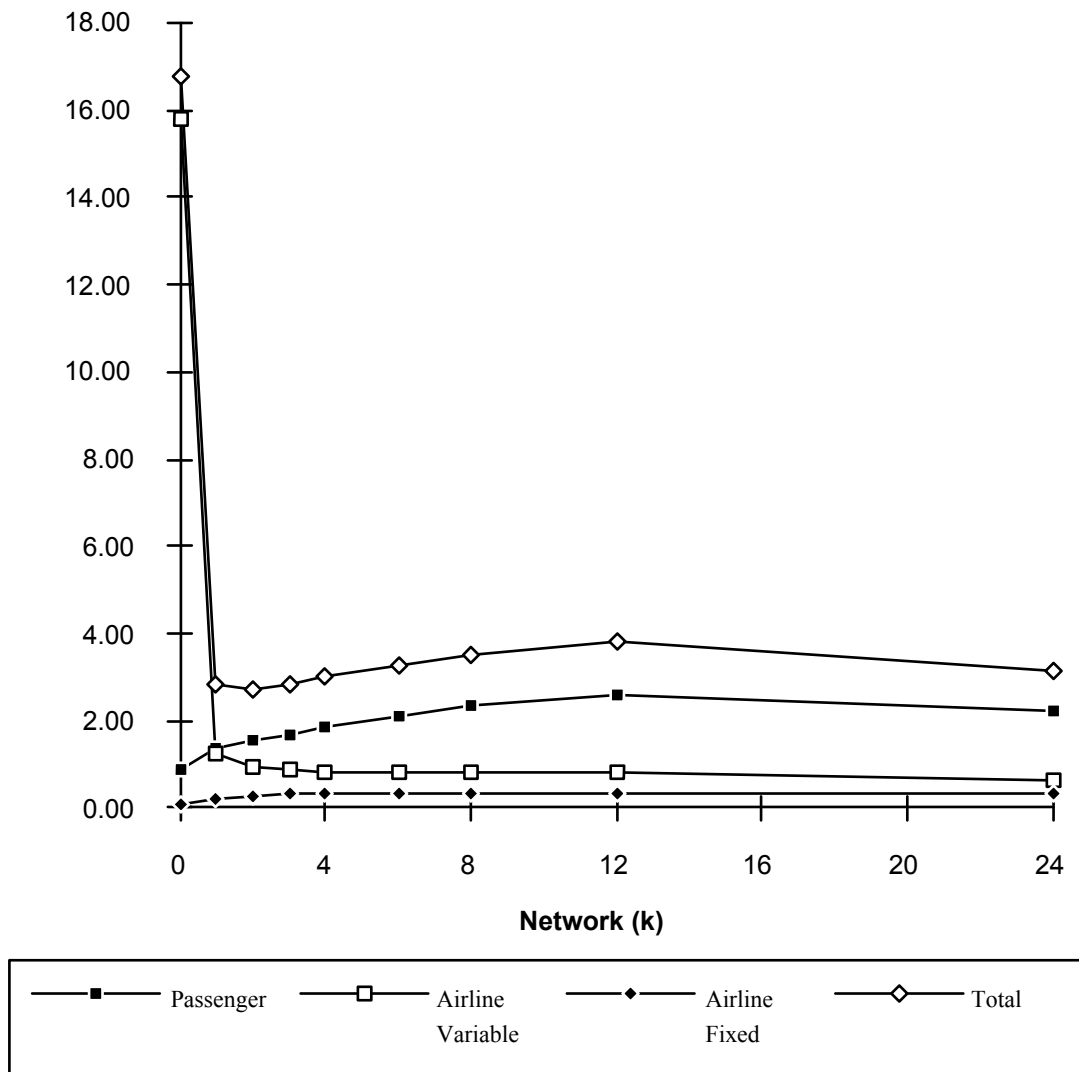
Passenger Time Is Minimized By Direct;
 Hub and Spoke Is 70% Higher

Similarly, Consider The Components of The Airline's Cost

- Fixed Aircraft Cost
 - Capacity, Not Use Related
- Variable Aircraft Cost
 - Use Related
- Per Passenger Cost

Putting All The Pieces Together:

Cost Components For Networks



For: $R = 500$ miles, $\rho = 25$ passengers/day,
 $v = 400$ miles per hour, $g = .25$ hours, $\alpha = .8$, $\lambda = 12$,
 $f = 12$, and $n = 24$ cities. Passenger Cost= \$20/hour.

k=2 Split Routing Minimizes Cost.

Contributions:

To Determine Optimal Network Must Consider Both
Airline and Passenger Costs

All Networks Types Can Be Optimal For Selected
Parameters

Network Affects Frequency and Reliability

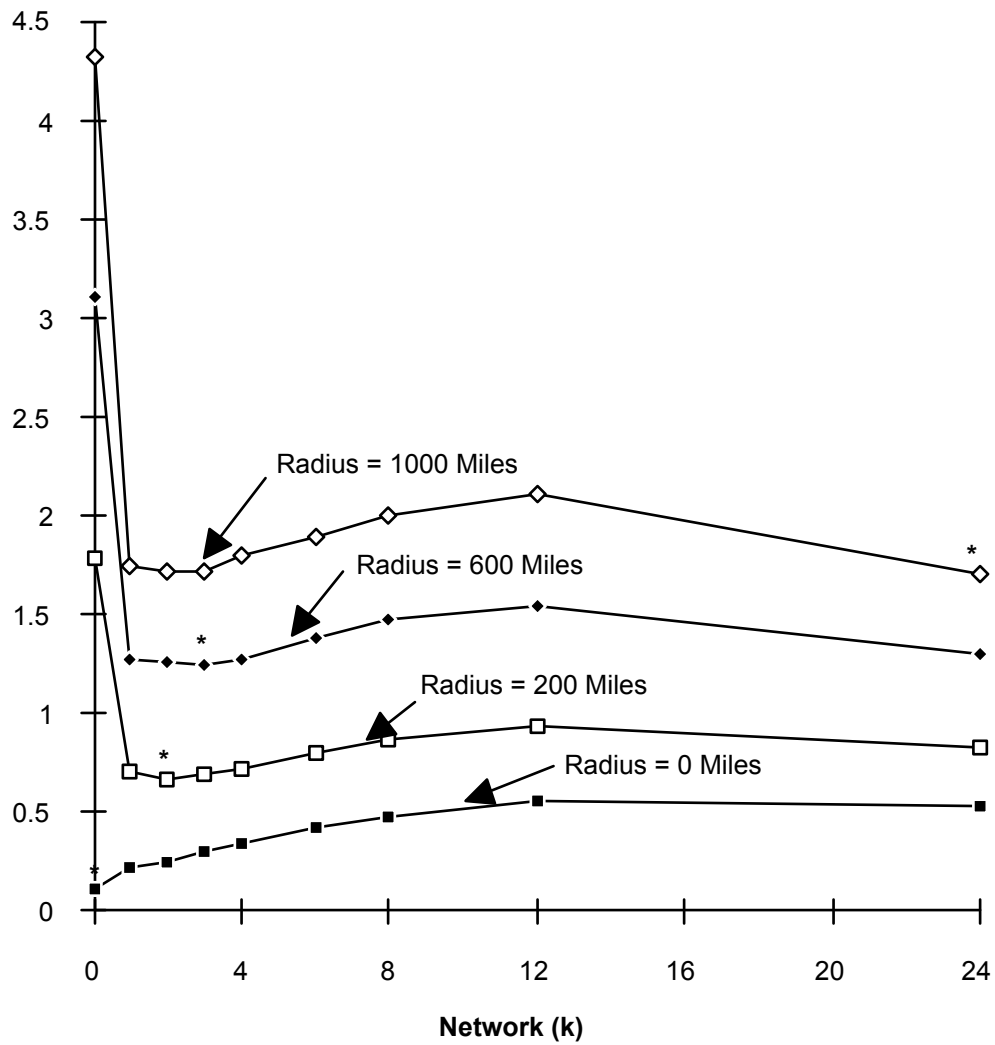
Direct Has The Lowest Frequency, But Highest
Schedule Reliability

Hubs Have High Frequency But Low
Schedule Reliability

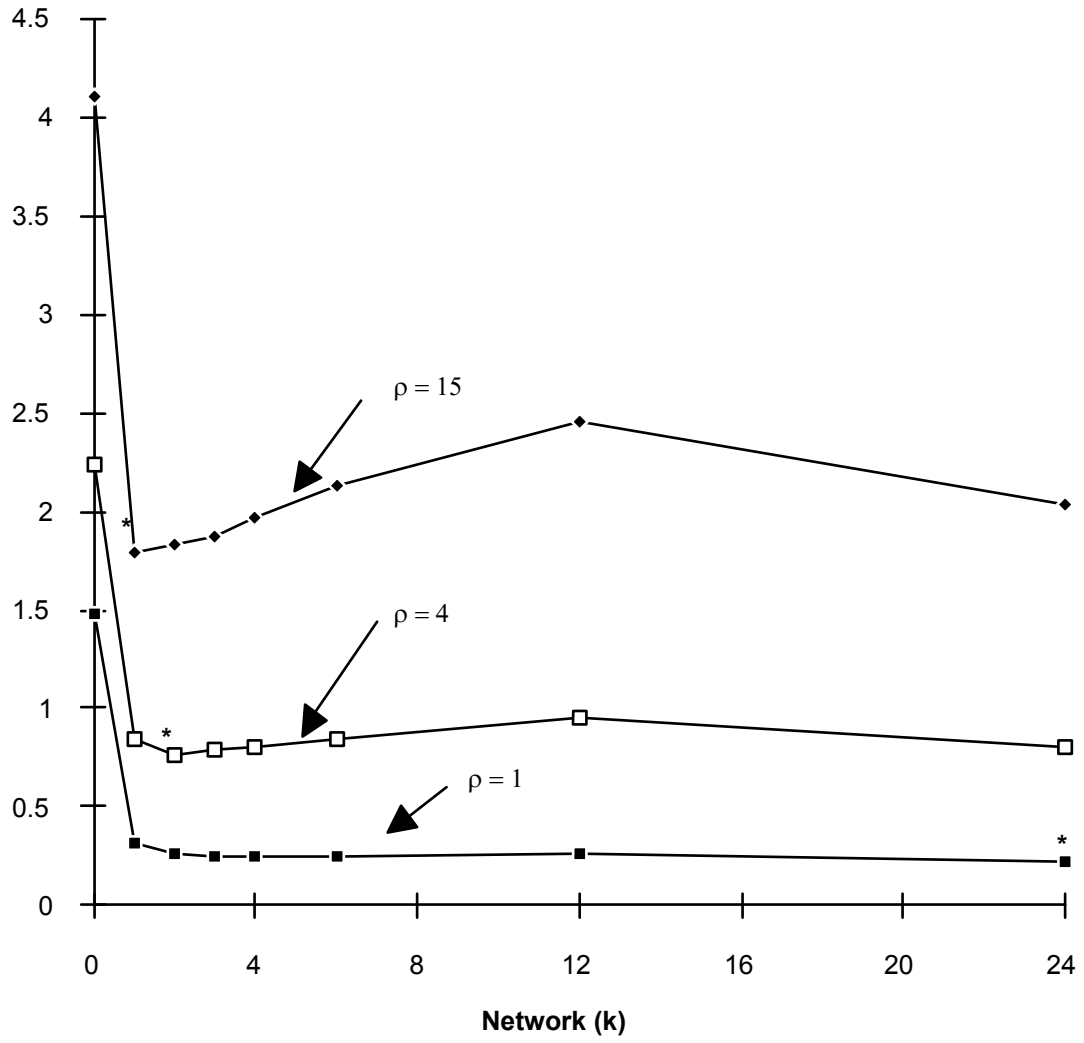
Parametric Analysis

Effect of Radius, Demand Rates and Number of Cities On Optimal Networks

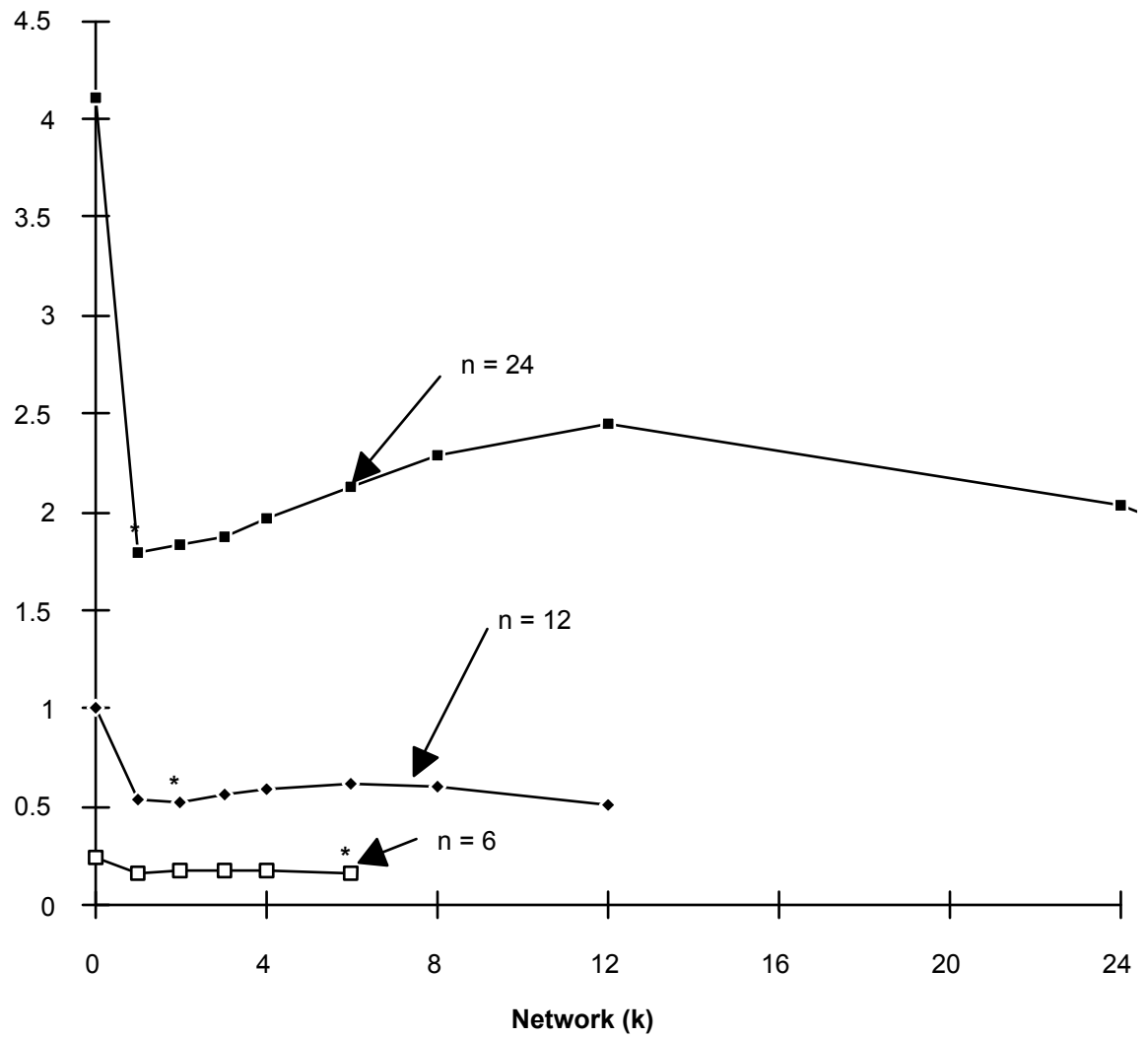
Optimal Network As A Function of Radius



Optimal Network As A Function of Demand Rate



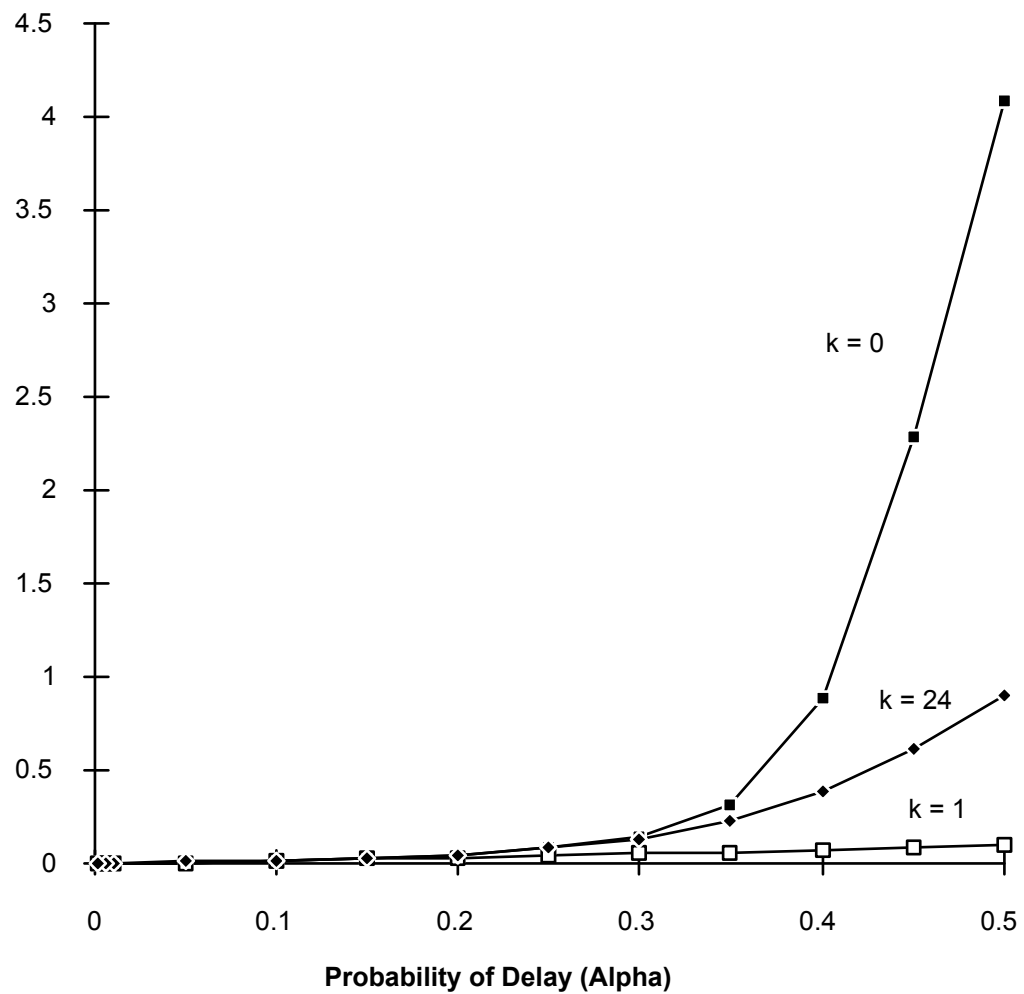
Optimal Network As A Function of Number of Cities



Optimal Choice of Schedule Reliability

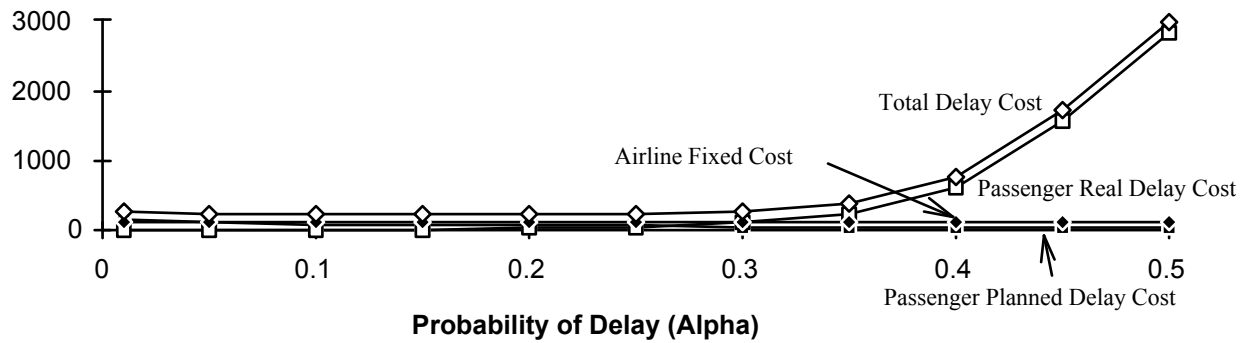
We Now Consider The Costs of Late Arrival,
Choosing α To Minimize Costs

Passenger Real Delay As a Function of Probability of Delay

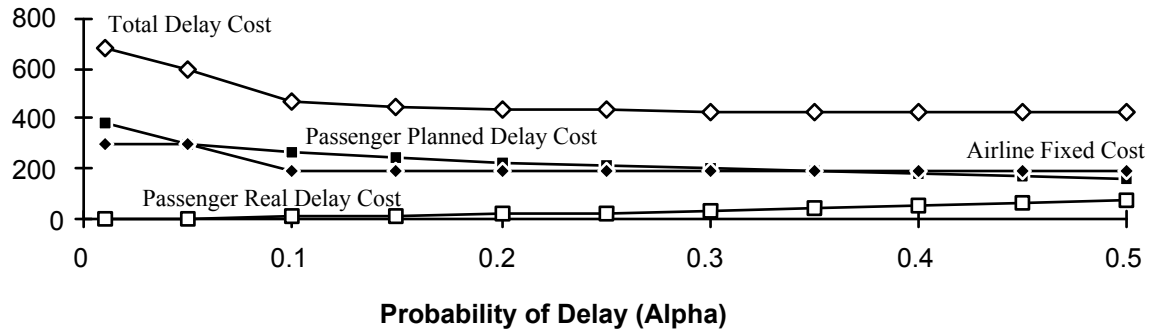


Total Delay Cost As A Function of the Probability of Delay For Three Networks

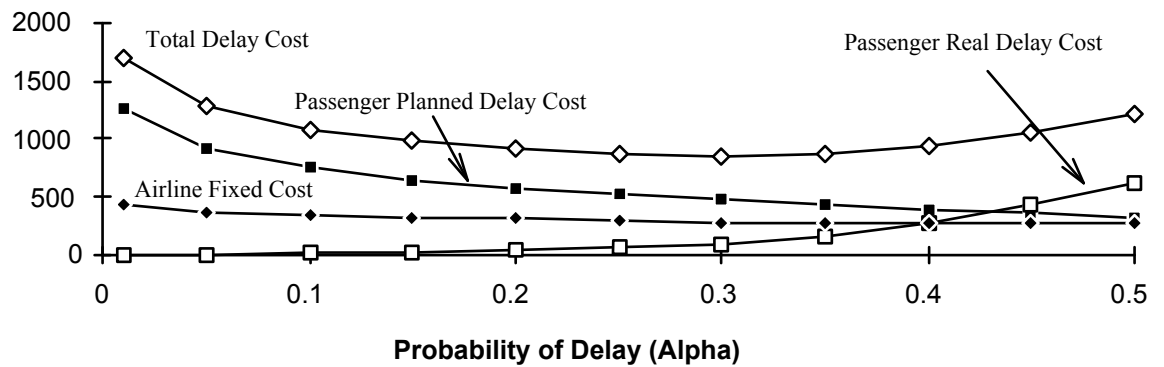
Direct Routing (k=0)



Hub and Spoke (k=1)



Tour Network (k=24)



Conclusions:

Direct Service Offers the Highest Reliability
 Hub Customers Prefer Low Reliability

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14. ABSTRACT The existing U.S. hub-and-spoke air transportation system is reaching saturation. Major aspects of the current system, such as capacity, safety, mobility, customer satisfaction, security, communications, and ecological effects, require improvements. The changing dynamics - increased presence of general aviation, unmanned autonomous vehicles, military aircraft in civil airspace as part of homeland defense - contributes to growing complexity of airspace. The system has proven remarkably resistant to change. NASA Langley Research Center and the National Institute of Aerospace conducted a workshop on Transportation Network Topologies on 9-10 December 2003 in Williamsburg, Virginia. The workshop aimed to examine the feasibility of traditional methods for complex system analysis and design as well as potential novel alternatives in application to transportation systems, identify state-of-the-art models and methods, conduct gap analysis, and thus to lay a foundation for establishing a focused research program in complex systems applied to air transportation.						
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