THE AERONAUTICAL DATA LINK: TAXONOMY, ARCHITECTURAL ANALYSIS, AND OPTIMIZATION

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Abstract

The future Communication, Navigation, and Surveillance/Air Traffic Management (CNS/ATM) System will rely on global satellite navigation, and ground-based and satellite based communications via Multi-Protocol Networks (e.g. combined Aeronautical Telecommunications Network (ATN)/Internet Protocol (IP)) to bring about needed improvements in efficiency and safety of operations to meet increasing levels of air traffic. This paper will discuss the development of an approach that completely describes optimal data link architecture configuration and behavior to meet the multiple conflicting objectives of concurrent and different operations functions. The practical application of the approach enables the design and assessment of configurations relative to airspace operations phases. The approach includes a formal taxonomic classification, an architectural analysis methodology, and optimization techniques. The formal taxonomic classification provides a multidimensional correlation of data link performance with data link service, information protocol, spectrum, and technology mode; and to flight operations phase and environment. The architectural analysis methodology assesses the impact of a specific architecture configuration and behavior on the local ATM system performance. Deterministic and stochastic optimization techniques maximize architectural design effectiveness while addressing operational, technology, and policy constraints.

1 Introduction

The purpose of the future CNS/ATM system is safe, efficient, and expeditious movement of aircraft in the airspace. In order to achieve this purpose, the CNS/ATM system (see Figure 1) will rely on global satellite navigation as well as ground-based and satellite-based communications via multi-protocol networks (e.g., the combined Aeronautical Telecommunications Network (ATN)/Internet Protocol (IP)) to bring about needed improvements in efficiency and safety of operations to meet increasing levels of air traffic [1]. Necessarily, these improvements must meet stringent accuracy, integrity, availability and continuity of function requirements as evidenced by the rules, regulations and standards established by the Federal Aviation Administration (FAA), the International Civil Aviation Organization (ICAO), the Radio Technical Commission for Aeronautics (RTCA), the Airlines Electronic Engineering Committee (AEEC), and various other contributing groups and consortiums.

The primary elements of the CNS/ATM system are airspace; air navigation facilities, equipment and services; airports and landing areas; aeronautical information and services; rules, regulations, and procedures; data link information and technologies;

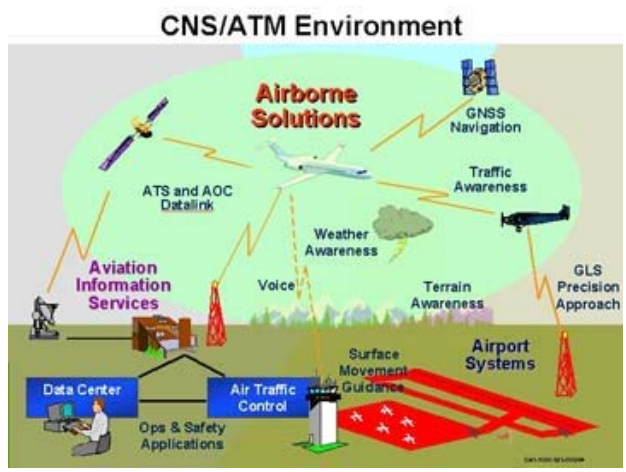

Figure 1. CNS/ATM Environment

and work force, including flight crews, air traffic controllers, and traffic managers [2]. The ATN will be the complex, global aeronautical network that will integrate CNS/ATM system components with ground networks and automation systems in order to provide seamless, interoperable data

communications around the world. At present, there are very few intuitive tools and objective methodologies in place that can aid a diverse set of users in analyzing or optimizing large complex data link architectures that are ATN compliant.

This paper will discuss the development of an approach that completely describes optimal data link architecture configuration and behavior to meet the multiple conflicting objectives of concurrent and diverse operations functions. The approach is premised on the development of a formal taxonomic classification of CNS/ATM systems, services, requirements and technologies. This taxonomy authorizes a coherent methodology for data link architectural analysis from a top-down perspective and/or a bottom-up perspective. Additionally, the process permits the use of deterministic and stochastic optimization tools including the use of Bayesian network scoring techniques to manage decision uncertainty as well as tools used to address trade-off concerns particularly between competing data link architectural configurations. The practical application of the approach enables data link users, developers, manufacturers, and integrators to assess the effectiveness and integrity of particular architectural designs while simultaneously addressing flight objectives, requirements and informational services.

1.1 ATN Background

Data link, the conduit that enables information transfer in the fluid world of aviation, is a network that allows for increased digital transmission of data to various users within the National Airspace System (NAS) with greater efficiency, reliability and ease. By managing and exchanging information and services between air-to-ground and air-to-air systems, the data link conduit enhances safety, improves operational efficiency, and increases capacity to all users in the global aviation environment. The backbone of the data link communication infrastructure will be composed of multiple independent subnetworks (or air/ground data links) including Mode S, Satellites and VHF Radio links. The global network that will “glue” or bind these data links with ground networks and automation systems to provide seamless, interoperable, point-to-point data communications is the ATN. The ATN will accomplish this interconnectivity and information routing using the Open Systems Interconnect (OSI) layered communications protocols [3]. Within the 7 OSI layers, the top four layers (i.e., application, presentation, session, and transport) are referred to as “upper layers” and the bottom three layers (i.e., physical, data link, and network) are referred to as the “lower layers”. There is also considerable interest in adopting the IP as the global aeronautical network [1]. The IP differs from the ATN primarily in the upper four OSI layers. The lower three 3 layers are common to both. It is in the lower layers where various data links utilize different techniques and protocols.

1.2 Analyzing Data Link Architectures

In order to design, configure, and analyze data link systems and architectures that are ATN- (or IP) compliant, future airspace users will have to understand the intricacies of data link complexity. This necessarily involves understanding various data link services (applications), numerous data link technologies, detailed protocols, and sundry airspace regulations as well as spectrum limitations. Various data link applications, for instance, impose very different communications requirements in terms of latency, coverage, capacity, integrity, and Required Communication Performance (RCP). These issues must be acknowledged and addressed in any system that will comply with the ATN and other communications protocols. The problem for future airspace users is making objective and meaningful decisions when configuring the required informational infrastructure needed and when selecting compatible data link functions, services and technologies to implement the infrastructure. Additionally, modeling and simulation capabilities will need to be incorporated in the decision process in order to assess data link integrity and its impact on the ATN and the CNS/ATM system. A system designer, for instance, will need to employ tools with sufficient modeling power and convenience to capture the complex behavior of a large system of functionally diverse subsystems while still affording timely and efficient data link analysis. Analyzing, selecting and configuring data link components and architectures that meet or improve critical information exchange is a complex decision analysis problem particularly when constrained by cost-effectiveness and unbiased objectivity.

1.3 Problems with the Current Process

Airspace users who desire to utilize data link services or technologies to solve particular problems currently acquire government, academic, or commercial experts who are proficient with any number of data link solutions. In general, these experts use their expertise to extract user requirements and then design or select a data link system (a component or architecture) whose implementation fulfils the requirements. There are, however, problems with this process for data link solution selection. First, the process is ad hoc, that is, there is not a widespread objective framework by which to analyze and assess data link solution performance. Second, the current process inherently involves the possibility of missing information. Overlooking (purposely or unintentionally) available information in a complex decision analysis tends to increase solution uncertainty. Third, there is always the ever-real danger of homing in on a particular solution too fast. This generally stems from previous user experiences with particular solutions as well as user impatience. Fourth, users often have difficulty framing their problem statement or they become confused when analyzing expert reports and are not able to determine which questions to ask and where to ask them. Fifth, there is general ignorance of how to apply formal tools to aid in analyzing scenarios for decision validation. Sixth, there is the possibility of the decision-maker being biased by economics, external relationships with solution providers, or other legitimate influences that do not permit objective decision analysis. For these reasons, there needs to be an objective methodology that allows users to analyze data link configuration and behavior in the presence of multiply conflicting objectives. The process must permit the use of formal tools to allow users to select optimal data link functions, services and technologies that meet safety, integrity and operational requirements.

1.4 Assumptions and Organization

There is an explicit assumption that a data link database exists and is populated with relevant, accurate and complete informational content for each taxonomic classification area. Although, in reality, such a database does not exist as a single entity, the data that would comprise it exists in distributed locations. Methods and techniques that create a virtual database from distributed sources exist [20]. The assumption is thus realistic in some future time. Additionally, the acquisition of assessment tools is outside the scope of the methodology.

This paper is organized as follows. Section 1 (the introduction) provides background information on the ATN and the motivation that guided the development of the data link decision framework. Section 2 (the decision framework) will describe, in detail, the various components of the methodology, including the taxonomy, architectural analysis, uncertainty management, and optimization technique for competing solutions. Section 3 (an example) will apply the decision analysis process to a Small Aircraft Transportation System (SATS) Operational Concept. Though the SATS example will be limited in scope, the analysis will provide sufficient insight into how to pose “what if” questions, where to incorporate external analysis tools, ways to manage decision uncertainty, and techniques used to select optimized data link architectures in the presence of conflicting constraints.

2 Data Link Decision Framework

This section will discuss, in detail, the components of the data link decision framework. The framework is intended to be a decision aid that can be utilized by a diverse set of users. The partitioned structure of the framework allows users with vastly different goals to become engaged in the methodology. User goals determine the level of involvement as well as the type of assessment to be employed.

2.1 Decision Framework Description

The data link decision framework is a decision analysis tool that aids users in obtaining optimized data link architecture configurations and behaviors. The primary components include a taxonomy of data link services (applications) and technologies, a multi-dimensional database that contains the taxonomic content, and a formal decision methodology that incorporates the use of applicable tools and modeling techniques. Descriptions of assessment tools (and when they should be applied) will be provided.

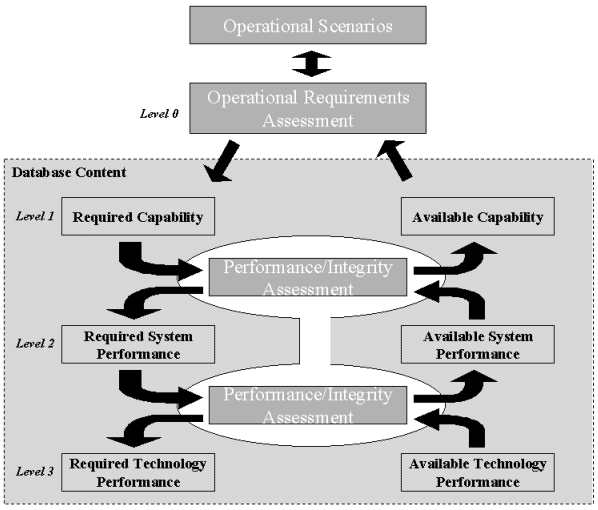

Figure 2. Data Link Decision Framework

2.1.1 The Data Link Methodology

The decision methodology in Figure 2 is a decision-analytic process that simplifies data link complexity by partitioning the analysis among four different levels (Levels 0-3). The vast amount of information required for objective and meaningful analysis is clustered in a multi-dimensional database organized according to a data link taxonomy. Conceptually, the process of data link solution selection can be posed as a multi-objective decision analysis problem. Using this modeling formulation, data link assessment can be characterized by a *p*-dimensional vector of objective functions

$$z(x) = [z_1(x), z_2(x), ..., z_p(x)] \qquad (1)$$

and a feasible region X where X is defined as

$$X = \{x : x \in \Re^n, g_i(x) \le 0 \text{ for all i}\}$$

and the constraints $g_i(x)$ are defined on an *n*-dimensional Euclidean vector space of decision variables, that is, $x = (x_1, x_2, ..., x_n) \in \Re^n$ with values in the set of real numbers, $\Re$. The goal of multi-objective analysis is to seek a set of "nondominated" solutions that are a subset of the feasible region X. Optimization in this context is not appropriate since one cannot, in general, optimize a priori a vector of objective functions. For this reason, the analysis will describe techniques that can be used for the selection decision in the presence of uncertainties. Deterministic and stochastic optimization techniques will be described when they can be used in an appropriate context.

Following the arrows in the decision methodology (Figure 2), each of the four levels partitions the multi-objective analysis from high-level constituents (mostly qualitative decision variables) to low-level constituents (quantitative decision variables). Level 0 involves information related to high-level operational concepts. Level 1 contains information capabilities (required and available) that guide data link services. Level 2 includes information (required and available) related to system level data link performance whereas Level 3 comprises information (required or available) related to various data link technologies. The traversal between levels (starting at Level 0) involves the acquisition of more detailed parametric information. The highest level (Level 0) can be thought of as a conceptual level whereas the lowest level (Level 3) consists of parameters that can be implemented in hardware.

Identifying the Informational Infrastructure

The transformation between Level 0 and Level 1 involves identifying and extracting the informational components required to perform the operational functions and the derivation of requirements necessary the enable the operational functions. Level 0 to Level 1 mapping establishes in a very basic form the informational infrastructure needed to support the required operations and operational functions. Data link services are then identified from this infrastructure. In order to interact at Level 0, the user needs to have, at a minimum, an operational concept containing operational requirements as well as other miscellaneous information (airport dependent, aircraft specific, ATC, and aircraft/vehicle controller information). The diagram in Figure 3 graphically depicts the Level 0 to Level 1 transformation process. It should be noted that informational components are the information required to perform the operational functions. Applicable tools for this transformation process include causal networks, dynamic programming, queuing models, etc.

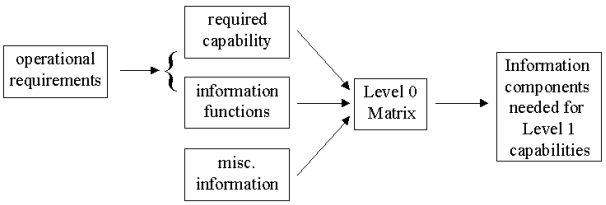

Figure 3. Level 0 to Level 1 Transformation

Identifying System Level Parameters

The transformation between Level 1 and Level 2 involves identifying the detailed system level performance requirements for the informational Infrastructure. A graphical depiction of this process is shown in Figure 4. In this diagram, system level data link information (from standards documents, etc.) is found in the data link database. Information in the reverse process (from Level 2 to Level 1) can be extracted from experiments and reports that are also contained in the database.

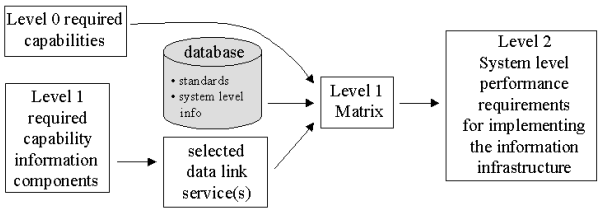

Figure 4. Level 1 to Level 2 Transformation

Identifying Technology Parameters that Enable System Behaviors

In general, the conversion between Level 2 (system parameters) and the technology parameters in Level 3 (transformation not shown) is difficult. It requires a model that describes how technology performance parameters functionally relate to system behavior. Designers and computational developers with intimate system knowledge and technology expertise who desire to develop hardware performance parameters from system level data link parameters primarily use this transformation. Information in Level 3 includes technology parameters described in the 3 lower OSI layers (e.g., modulation, bit error rate, etc.). The reverse process (from Level 3 to Level 2), not shown, describes system behaviors that are possible from particular data link technologies.

2.1.2 Top-Down versus Bottom-Up Scenarios

This decision framework authorizes a practical and coherent approach for data link architectural analysis from both top-down and bottom-up perspectives. The top-down perspective (scenarios ➔ operational requirements ➔ required capabilities ➔ required system performance ➔ required technical performance) allows a user to formulate a data link design concept and then successively refine the capability, system and technology requirements. In a bottom-up perspective (available technical performance ➔ available system performance ➔ available capabilities ➔ operational requirements ➔ scenarios), the user acquires data link technologies already available and gradually builds larger system level architectures. Clearly, mature design is some combination of top-down and bottom-up analysis. With reference to Figure 2, top-down analysis involves traversing from Levels 0 to 1, Levels 1 to 2, and/or Levels 2 to 3. In like manner, bottom-up analysis involves the reverse, that is, Levels 3 to 2, Levels 2 to 1, and/or Levels 1 to 0.

2.2 Data Link Taxonomy

2.2.1 The Need for a Formal Taxonomy

Given the vast demand of information required for airspace operations, there has been a need to provide a tool for classifying this information in a manner that is both meaningful and useful. The data link taxonomy (Figure 5) is organized hierarchically, that is, from conceptual to implementation information types (Levels 0 to 3, respectively). The taxonomy is also relational in that all the information on one level is mapped vertically to each adjacent level as well as horizontally to elements and parameters on the same level.

2.2.2 Data Link Taxonomy Description

The data link taxonomy (Figure 5) has the following major partitions: operation scenarios, operational functions/capabilities, information capabilities, data link services, technology requirements, and various data link technologies. Taxonomy content (Figure 5) is linked with levels in the decision methodology (Figure 2) in the

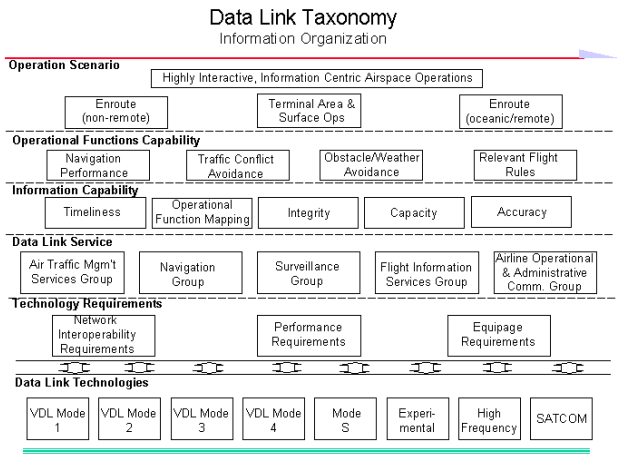

Figure 5. Data Link Taxonomy

following way: Level 0 includes operation scenarios and operational function/capability information, Level 1 contains information capabilities, Level 2 comprises data link services, and Level 3 encompasses information related to technology requirements and data link technologies. To transition between the levels in the decision methodology (Figure 2), there is an information transformation matrix that must be tailored per data link assessment. Examples of these will be shown in the SATS example (described later in section 3). Elements of each transition matrix will be comprised of instantiated information described in subsection 2.1.1 (depending on the type of analysis performed). This instantiated information will include data link taxonomic content related to data link services, functional capabilities, etc. The information in figure 5 describes general categorical information. Data link services, for example, are subdivided further into groups: the ATC group, the Navigation group, the Surveillance group, the ATS group, and the Airline Operations group. Each of these groups can be partitioned further. In similar fashion, the data link technology partition captures detailed information related to a large selection of technology solutions such as VHF Data Link Mode 1 (VDLM1), VDLM4, VDLMS, UAT, SATCOM, etc. The parameters, constraints, and guidelines associated with each data link capability (service), operational phase, technology solution and so on are contained in the database.

2.2.3 The Multi-Dimensional Database

The data link database is multi-dimensional to best accommodate the information content and relational aspects of the data link taxonomy. For proper analysis, the database is intended to be accurate and complete. Information that will be used to populate the database will come from data link equipment manufacturers and experimental testing reports. Information contained in data link standards documents (e.g., RTCA MOPS, MASPS, etc.) will also be included.

2.3 Architectural Analysis

Architectural analysis is the process of utilizing analytical tools to answer qualitative or quantitative questions regarding data link architectures (whether informational, system-level, or technology-based). Given the combinatorial explosion of the decision variables, there are a large number of possible architectures from which to choose. Simply stated, the process of finding a candidate set of functionally compatible architectures involves identifying the data link services (applications) required, determining the constraints used to confine the feasible region of solutions, and applying an analytical tool to select the most desirable candidate from the set.

2.3.1 Top-Down Scenarios

In top-down analysis, the user has higher-level information and/or concepts and wants some lower level component that behaves in such a way as to satisfy the goal. The goal here is to instantiate the higher-level informational components by traversing from Levels 0 to 1, Levels 1 to 2, and/or Levels 2 to 3 depending on the depth of specificity. For instance, let's say a user knows the capabilities required and wants to determine the system parameters required to instantiate the capabilities. The user would employ the Level 1 to Level 2 information transformation matrix, which requires information related to required capabilities as well as information parameters suitable for those capabilities (i.e., timeliness, integrity, and accuracy parameters). The information transformation from Level 1 to Level 2 (Figure 4) would also require additional information obtained from the database to produce system level parameters whose behavioral performance conforms to the required Level 1 capabilities. When more than one set of

information parameters satisfies the user's required capabilities, the final selection can be arbitrary or can be made using tools appropriate for competing solutions. An example of top-down analysis is described in section 3.

2.3.2 Bottom-Up Scenarios

In bottom-up analysis, the user has one or more lower-level components or parameters that are available and wants to determine higher-level descriptive performance characteristics. In real-world cases, this is accomplished through exhaustive testing or insightful experiments. Information required to perform bottom-up analysis can be reasonably obtained. An example of bottom-up data link analysis (Level 3 to Level 2) is described by Jones [4]. In this report, Jones produces system level performance behavior of a VDL Mode 2 data link technology using the Petri Net formalism. When more than one set of components (an architectural unit) satisfies the needs of the user, trade-off analysis tools can help to manage decision uncertainty.

2.3.3 Combined Analysis

In many real-world scenarios, combined analysis (top-down and bottom-up) is preferable. Using this approach, a user employs top-down analysis to select capabilities and operational functions that enable higher-level requirements. Similarly, bottom-up analysis is used to determine technologies and system-level performance parameters currently available to meet the required capabilities. Advantages of a combined approach include the identification of gaps between the higher-level requirements and lower level suitable technologies. The gaps can then be addressed by design or by standards. An example of the combined approach (Level 0 to Level 2 and Level 3 to Level 1) can be found in the Technology Evaluation Report for the Airborne Internet (AI) performed by CNS, Inc. [5]. In this report, candidate AI architectures were developed from a combined perspective, that is, using AI (top-down) requirements and potential communication and networking technologies (bottom-up).

2.4 Competing Solutions and Analysis Tools

Whether the analysis is guided from a top-down, bottom-up, or combined approach, the possibility of competing solutions will always be present (except for the trivial case). When several candidate solutions sets are revealed as a result of an analysis, the user needs some technique or process that selects the most desirable candidate from the set. When all the required data is present to evaluate an informational, system, or technology architecture, techniques can be employed to make the selection decision with certainty. This is generally called optimization. However, there are various decision analysis problems that are made under uncertainty. More often than not, this latter case exists for complex decisions and thus requires more input from the user to guide the selection process. There are also times when several candidate solution sets can be used with no one superior choice. Techniques in this case incorporate the ability to address trade-offs between competing solutions.

2.4.1 Optimization Tools

When the user is faced with a selection decision, optimization tools may be appropriate. Optimization models are sets of mathematical relationships that represent, or approximate, a real situation. These models can be used to choose a particular candidate solution from a set of possible solutions particularly when the goals of the user are achievable. Various optimization techniques that can be used in this context include linear programming, network flow models, critical path models, shortest path models, integer-programming formulations, and nonlinear programming models.

Generally, when all the decision variables are known and the user's goal is clear, deterministic optimization techniques are appropriate. However, if all the inputs to the problem are not known or forecasting is utilized, then stochastic optimization (such as Petri Net models [6], discrete-event simulation tools and Monte Carlo techniques) should be used.

2.4.2 Managing Decision Uncertainty

Decision making under uncertainty is the condition that exists when there is missing information, some of the decision variables are qualitative in nature, forecast models are employed, there is considerable complexity involved, or the problem to be solved is multi-objective. Regardless of the specifics, analyzing problems that include

uncertainties frequently involve choosing among alternative options, using probability assessments to encode uncertainties, identifying causal dependencies that exist in the process, quantifying the value of information, and determining acceptable levels of risk. Some of the tools that can be used to manage decision uncertainty include decision trees, influence diagrams, Bayesian networks, utility functions, goal programming, and sensitivity analysis to name a few [7].

With respect to the decision analysis methodology (Figure 2), uncertainty generally exists to a greater degree in the upper levels of the framework (Levels 0 and 1). This is due primarily to the qualitative nature of operational scenarios, the impact of inadequate requirements, and the evolving function of data link capabilities and standards. Uncertainty also exists (to a lesser degree) in the lower 2 levels (Levels 2 and 3). Its presence becomes manifest when required information is missing, when a user's subjective preferences are inadequately quantified, and when specific environmental factors (weather, airspace density, loading, legal, cost) that influence the selection decision are hard to acquire.

2.4.3 Addressing Trade-Offs

Whenever one candidate solution is not clearly superior to others in a set or there are advantages and disadvantages to each solution, trade-off analysis should be employed. Trade-offs provide a mechanism to mitigate the risks of data link solution acceptance by selecting a candidate solution that minimizes undesirable performance characteristics while maximizing its benefits. Regardless of where trade-off analysis is implemented in the decision framework, its application is integral to the data link evaluation process. Some of the techniques used for trade-off analysis include Saaty's Analytical Hierarchy Process (AHP) [8], multi-attribute utility theory (MAUT) [9], iterative techniques (multi-objective programming, goal programming, and Pareto optimality), and outranking techniques. Trade-off analysis is covered in the general area of multi-criteria decision analysis (MCDA) [10]. An interesting example of trade-off analysis applied to data link architecture selection (Level 3 to Level 0) is described by Koczo [11]. In his process to evaluate integrated airport surface operations, Koczo examines possible allocations of CNS/ATM data link applications to respective data link candidates. He uses these allocations to postulate a set of candidate data link architectures for Terminal Area Productivity (TAP). In his analysis, he uses trade-offs to determine the suitability of various data link architectures optimized by resource usage and capabilities required.

2.4.4 Bayesian Network Scoring

A promising tool that can be used for a number of purposes in the data link decision analysis framework is the Bayesian Network Scoring technique. This acceptance methodology utilizes a Bayesian network (BN) as a globally coherent model and employs trade-off analyses in order to select optimal data link candidates subject to various constraints in the presence of uncertainty. The technique has been used previously as an acceptance methodology for commercial-off-the-shelf (COTS) software [12] and as an independent assessment tool for selecting COTS components in the Shuttle [13]. Bayesian networks are directed acyclic graphs (DAGs) in which the nodes represent decision variables, the arcs signify the existence of direct causal influences between the variables, and the strengths of these influences are expressed by forward conditional probabilities [14]. In the context of data link architectures, the methodology is intuitive, uses probabilities to encode uncertainties, and incorporates the use of trade-offs.

The Bayesian network in Figure 6 can be used to illustrate the process of accepting suitable data link architectures from a set of candidate solutions. In this example, the decision analysis is performed between Levels 2 and 1 using a bottom-up perspective, that is, the user desires to find the data link architecture that best optimizes the required capabilities. It is assumed that the system-level parameters and a Bayesian network structure (that represents how system-level parameters influence data link capabilities) have been previously acquired or computed. For each candidate architecture, the BN would input its system-level parameters and then propagate this information into the network to produce probabilistic scores for each of the required capabilities (BN outputs). Multi-criteria decision analysis tools would then be used to make trade- offs between each product's scores. This phase is used to incorporate a user's data link

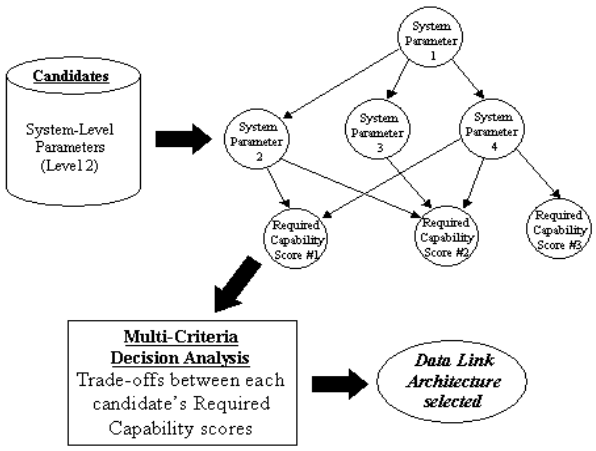

Figure 6. Data Link Bayesian Network

capability preferences (in a multi-objective sense). The result of which is a selected data link architecture that meets required capabilities while simultaneously incorporating user preferences.

3 Example Data Link Analysis ➔ SATS CONOPS

The following example applies the data link analysis framework described in the preceding sections to a proposed operations scenario. The scenario is one of the four operating capabilities of the Small Aircraft Transportation System (SATS) concept currently under development by NASA, the FAA, and local aviation and airport authorities. A draft Concept of Operations (CONOPS) document [16] defines the 2010 SATS consisting of

- Higher Volume Operation (HVO) at Non-Towered/Non-Radar Airports,
- Lower Landing Minimums at Minimally Equipped Landing Facilities,
- Increased Single-Pilot Crew Safety and Mission Reliability, and En Route Procedures, and
- Systems for Integrated Fleet Operations.

The decision analysis framework will be applied to the HVO capability.

As described above, the framework is a decision support tool that guides the decision process in both top-down and bottom-up directions. The top-down direction translates operational requirements into increasingly detailed information requirements from desired data link capability through data link system performance requirements to implementation technology performance requirements. The bottom-up assessment delineates and selects data link capability options from available technologies. The framework consists of four levels designated zero through three. Each level is a matrix whose elements are the quantitative performance requirements for the next level. The tool is designed such that a decision process can be initiated at any level or conducted in any direction, depending on the required decision and the available data.

The objectives of the HVO application are to derive the required operations and operational functions from the CONOPS, determine the quantitative information performance required to support the operational functions, determine the data link capabilities needed to provide the information performance, and determine the capability's system performance requirements. The application is a Level 0 through Level 2 top-down process resulting in the selection of a data link service and a confirmation of its capability to provide the information performance to support the required operations. The transition to Level 3 (Figure 11), which specifies the performance of the underlying technology in terms of the bottom three OSI layer parameters, is not done. The transition requires models, tools, and expertise that the authors do not currently possess. An alternate approach that can be used to model the available underlying technologies (i.e. VDL Modes 1 through 4, Mode S, etc.) in terms of the OSI parameters is to simulate the selected data link operation and then collect system performance data for the Level 2 information elements. A comparative analysis of the Level 2 solutions (resulting from this bottom-up approach) and the top-down Level 2 results would be performed to select the optimum implementing technologies. Tools are available to perform the modeling and analyses [7, 17].

The information in the Level 0 matrix for HVO (Figure 7) is derived from the draft SATS CONOPS 2010 document [16]. The matrix encapsulates the required operations (horizontal label), the functions necessary to complete the operations (vertical label), and the performance parameters required to execute the functions (matrix elements). In order to transition to Level 1, estimated values for the performance parameters are required. The estimation techniques can range from back-of-the-envelop calculations to high fidelity modeling and simulation [18, 19] depending on the preferences

Supported Operations

HVO Operational Requirements - Level 0

Operational Function	Required Operation						
	File HVO/IFR Flight Plan	Departure/ Arrival Request	Departure/ Arrival Assignment	Takeoff/ Approach	Transition To/From ATC		
Traffic Density		# Aircraft	# Aircraft				
Op. Time Window							
Requested Nav. Parameters • Dep/Arr Fix • Dep./Arr. Time • A/C State		Req'st Signal Dest. Pos. Time Pos./Vel.					
Assigned Nav. Parameters • Sequence • Dep./Arr. Time • Velocity			Queue Pos. Time 1st Leg Vel.				
Self-Sequencing				Traj. Intent	Traj. Intent		
Self-Separation				Req'd Nav. Perf. Acc'y. (nm, kts)			
Release To/From ATC					Sig. Acq. Range		

Figure 7. Level 0 Matrix

Estimation of Level 0 Performance Parameters

Information Performance Requirements - Level 0

Performance Parameter	Operational Function																	
	Operation Time Window	Requested Navigation Parameters				Assigned Navigation Parameters				Self Sequencing				Self Separation				Release To/From ATC
Aircraft #		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
Initial Velocity (kts)	15 min	120	120	120	120													
Initial Velocity (kts)	17.5 min	104	104	104	104													
Initial Velocity (kts)	20 min	93	93	93	93													
Leg 1 Dist. (nm)		25	24	25	26													30 nm
Leg 1 Time (min)	15 min	12.5	11.9	12.5	13													
Leg 1 Velocity (kts)	15 min					120	120	120	120									
Leg 1 Velocity (kts)	17.5 min					104	104	104	104									
Leg 1 Velocity (kts)	20 min					89	89	89	89									
Leg 1 NP (nm)	15 min													0.1	0.1	0.1	0.1	
Leg 1 NP (m/s)	15 min													0.3	0.3	0.3	0.3	
Leg 2 Dist. (nm)										12.5	10	12.5	15.2					
Leg 2 Rel. Hdg. (°)										22.2	0.0	-22	31.3					
Leg 2 Time (min)	15 min									6.25	5	6.25	7.6					
Leg 2 Velocity (kts)	15 min									123	123	123	123					
Leg 2 Velocity (kts)	17.5 min									112	112	112	112					
Leg 2 Velocity (kts)	20 min									88	88	88	88					
Approach Vel. (kts)	15 min									80	80	80	80					
Approach Vel. (kts)	17.5 min									80	80	80	80					
Approach Vel. (kts)	20 min									80	80	80	80					
Leg 2 NP (nm)	15 min													1	1.5	1	.3	
Leg 2 NP (m/s)	15 min													10	10	10	10	

Figure 8. HVO 4 Aircraft Landing Operation

and rigor requirements of the user. For this example, a linear programming method called goal programming is used [21]. The primary reasons for selecting this method are the ability to model trajectories with multiple heading changes for any number of aircraft, the implicit computation of trajectory deviation while optimizing the performance parameter of interest, and the wide availability of computational tools for the method. Most commercial spreadsheet applications include optimization capability and there are several books [7, 17] that develop goal programming models within the applications.

The goal programming model for HVO is:

$$\min Z = \sum_i \left(d_i^- + d_i^+\right)$$

subject to:

$$X_{si} + .5\sec(\theta_i)t_i V_{ij-1} + .5\sec(\theta_i)t_i V_{ij} + d_i^- - d_i^+ = X_{Di}, \quad (2)$$

$$\begin{aligned} &V_{ij-1} \le V_{MAX}, \\ &V_{ij} \le V_{MAX}, \\ &V_{ij-1} \ge V_{MIN}, \\ &V_{ij} \ge V_{MIN}, \\ &i = 1, M \text{ and } j = 2i \end{aligned} \quad (3)$$

where

M = number of legs,

d_i^- = underachievement of the goal,

d_i^+ = overachievement of the goal,

X_{si} = initial position of Aircraft K for leg i,

θ_i = relative heading of leg i,

t_i = elasped time on leg i,

V_{ij} = velocity of Aircraft K at start of leg i,

V_{ij-1} = velocity of Aircraft K at end of leg i,

X_{Di} = destination of Aircraft K for leg i,

V_{MAX} = maximum speed for Aircraft K,

V_{MIN} = minimum speed for Aircraft K.

The model consists of a set of trajectory goals (2) for each aircraft involved in the operation(s). Each goal in an aircraft's goal set represents a distance and relative heading along one leg. Additional goals represent the bounds (3) on allowed aircraft velocities. The bounds are the lowest maximum and highest minimum velocity capability in the group of aircraft. The effect of the method is to determine the maximum velocity along each leg while minimizing the deviation from the goal position. The modeler inputs the elapsed time for each leg, and the distance and heading relative to the previous leg for each leg. The modeler also has the flexibility to constrain the deviations from the goal position to meet required navigational accuracy values.

For this example, the units of velocity are knots, the units of time are minutes, and the units of distance are nautical miles. An arbitrary two-leg trajectory including one trajectory change was drawn for each of four arriving aircraft. Under the HVO scenario, the distances, times, and relative headings for each first leg are derived from aircraft requests. The distances, times, and relative headings (inputs to the model) for subsequent legs are derived from the self-sequencing and self-

Data Link Service

Capability Requirements - Level 1

Information Requirement	Required Data Link Capability					
	Aid to Visual Acq.	Conflict Avoidance	Separation Assurance & Sequencing	Airport Surface	Flight Path Deconfliction Planning	Simultaneous Approach
Timeliness						
• Initial Acq(nm)	10	10	40	5	90	10
• Alert Time	N/A	2 min.	2 min.	5 sec.	4.5 min.	15 sec.
Integrity						
• Availability	95%	99.9%	99.9%	99.9%	95%	95%
• Nav. Integrity	95%	95%	95%	95%	95%	95%
• Related Traffic Density	21 (<10 nm)	6 (<20 nm)	120 (<40 nm)	150 (<5 nm)	30 (<90 nm)	32 (landing)
Accuracy						
• NAC_p(nm)	10	10	10	10	6	10
• NAC_v(m/s)	3	3	3	4	3	3

Figure 9. Level 1 Matrix

Data Link Application

Performance Requirements - Level 2

Information Element	System Performance Requirements – A2 Equipage																	
	Aid to Visual Acq.		Conflict Avoidance		Separation Assurance & Sequencing		Airport Surface		Flight Path Deconfliction Planning		Simultaneous Approach							
	Enroute-R	Enroute-NR	Terminal	Enroute-R	Enroute-NR	Terminal	Enroute-R	Enroute-NR	Terminal	Enroute-R	Enroute-NR	Terminal	Enroute-R	Enroute-NR	Terminal	Enroute-R	Enroute-NR	Terminal
State Vector																		
Accuracy																		
Update Rate																		
Acquisition Range																		
Latency																		
Mode Status																		
Update Rate																		
Acquisition Range																		
Air Ref. Velocity																		
Update Rate																		
Acquisition Range																		
Target State/Chg.																		
Update Rate																		
Acquisition Range																		
Availability																		
Integrity																		
Capacity																		

Matrix values found in ADS-B MASPS

Figure 10. Level 2 Matrix

separation functions. For this example, the leg distances are taken from the drawn trajectories and the leg times are distance-weighted divisions of the total time to complete the operation. This approach allows the modeler to vary the total time available for the operation. Additional assumptions are that the upper bound on velocity is 123 knots, the lower bound on velocity is 61 knots, the final velocity is a typical approach speed of 1.3 times the lower bound, and the desired solution requires common leg velocities for all aircraft. The method computes the velocities required at the beginning and end of each leg and the over and under deviations of aircraft position from each leg's target position. The input and computed values yield sufficient information to quantify the Level 0 information performance parameters. Figure 8 shows the estimated information performance requirements for a four-aircraft landing operation using three different operation completion times.

The transition to Level 1 requires the data link capability(ies) needed to provide the information performance derived in Level 0. The transition process is a search to map the Level 0 operational functions to data link service capabilities, and to confirm that the capabilities' timeliness, accuracy, and integrity meets the information performance requirements of Level 0. A manual search of RTCA Minimum Aviation System Performance Standards (MASPS) documents for data link services yielded the Level 1 matrix in Figure 9. For the HVO scenario, the data link service that provides the needed information performance capability is Automatic Dependent Surveillance Broadcast (ADS-B) [15]. An automated search

Data Link Application

Performance Requirements - Level 3

Performance Parameter	Technology Performance Requirements																	
	Aid to Visual Acq.		Conflict Avoidance		Separation Assurance & Sequencing		Airport Surface		Flight Path Deconfliction Planning		Simultaneous Approach							
	Enroute-R	Enroute-NR	Terminal	Enroute-R	Enroute-NR	Terminal	Enroute-R	Enroute-NR	Terminal	Enroute-R	Enroute-NR	Terminal	Enroute-R	Enroute-NR	Terminal	Enroute-R	Enroute-NR	Terminal
Layer 1-Modulation																		
Layer 1-Bit Rate																		
Layer 1-BER																		
Layer 1-BR/BW																		
Layer 1-Eb/No																		
Layer 1-Bb/T																		
Layer 1-D/U																		
Layer 2-MAC																		
Layer 2-DLS																		
Layer 2-LME																		
Layer 3-SNL																		
Layer 3-Msg. Content																		

Figure 11. Level 3 Matrix

process would be preferable to a manual search process for the transition to Level 1. The process would require the electronic availability of data link MASPS documents to a widely distributed information infrastructure, and an appropriate search engine. Wide area information network capabilities are proposed [20] that enable such an automated search process.

The Level 2 Matrix (Figure 10) defines the specific performance requirements of the information elements that provide the selected data link service's timeliness, accuracy, and integrity. The performance value of each information element that is required to enable each capability is available in the MASPS [15] for the selected data link service. For this example, the transition to Level 2 was also accomplished by a manual search, and the previous discussion about an automated search process apply to this level as well.

4 Conclusions

This paper discusses the development of an objective decision analysis framework that allows users to analyze data link configuration and behavior in the presence of multiply conflicting objectives. The approach is premised on the development of a formal taxonomic classification of CNS/ATM systems, services, requirements and technologies. The taxonomy authorizes a coherent methodology for data link architectural analysis. The process permits the use of formal tools to allow users to select optimal data link functions and services that meet safety, integrity and operational requirements. The methodology was applied to a SATS CONOPS document for Higher Volume Operations (HVO) at Non-Towered/Non-Radar Airports. The application provided sufficient insight into how to pose "what if" questions, where to incorporate external analysis tools, ways to manage decision uncertainty, and techniques used to select optimized data link architectures in the presence of conflicting constraints.

References

[1] Zernic, Michael, Freudinger, Lawrence, and Morris, A. T., "Aeronautical Satellite Assisted Process for Information Exchange through Network Technology (AeroSAPIENT) Project: The Initial Trials", *Proceedings from the IEEE Aerospace Conference*, Big Sky, Montana, March 10-17, 2001.

[2] Kayton, Myron, and Fried, Walter R., *Avionics Navigation Systems, 2nd Edition*, John Wiley & Sons, Inc., 1997.

[3] *ISO/IEC Information Technology-Open Systems Interconnection-Basic Reference Model: The Basic Model.* ISO/IEC 7498-1:1994.

[4] Jones, Rob, and Ciardo, Gianfranco, "On Phased Delay Stochastic Petri Nets: Definition and an Application", *Proc. of the 9th IEEE Int. Workshop on Petri Nets and Performance Models (PNPM'01)*, Aachen, Germany, Sept. 11-14, 2001.

[5] *Airborne Internet Technology Evaluation*, a Computer Networks & Software, Inc. report to NASA Glenn Research Center under NASA Contract No. NAS 3 99165, August 28, 2001.

[6] Murata, Tadao, "Petri Nets: Properties, Analysis and Applications", *Proceedings of the IEEE, vol. 77, no. 4*, April 1989.

[7] Winston, W. L., and Albright, S. C., *Practical Management Science: Spreadsheet Modeling and Applications*, Wadsworth Publishing Co., 1997.

[8] Saaty, T., *The Analytical Hierarchy Process*, McGraw-Hill, New York, 1990.

[9] Yoon, K., Hwang, C., *Multiple Attribute Decision Making: an Introduction*, Sage Pub., 1995.

[10] Lootsma, F., *Multi-Criteria Decision Analysis via Ratio and Difference Judgements*, Kluwer Academic Publishers, The Netherlands, 1999.

[11] Koczo, S., *Integrated Airport Surface Operations*, NASA/CR-1998-208441, July 1998.

[12] Morris, A.T., *COTS Score: An Acceptance Methodology for COTS Software*, 19th DASC, Philadelphia, PA., October 2000.

[13] Morris, A.T., and Beling, P.A., *Space Shuttle RTOS Bayesian Network*, 20th DASC, Daytona Beach, FL., October 2001.

[14] Pearl, J., *Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference*, Morgan Kaufmann Publishers, San Mateo, CA., 1988.

[15] *Minimum Aviation Systems Performance Standards for Automated Dependent Surveillance-Broadcast (ADS-B)*, RTCA/DO-242A, Draft 1, March 2, 2002.

[16] NASA, *Small Aircraft Transportation System, 2010 Concept of Operations Document*, Version 0.6, June 24, 2002.

[17] Ragsdale, Cliff T., *Spreadsheet Modeling and Decision Analysis, 3rd Edition*, South-Western College Publishing, 2001.

[18] Abbott, T. S., and Elliott, D. M., *Simulator Evaluation of Airborne Information for Lateral Spacing (AILS) Concept*, NASA TP-2001-210665, March 2001.

[19] McDermott, W. J., Maluf, D. A., Gawdiak, Yuri, Tran, P., *Secure Large-Scale Airport simulations Using Distributed Computational Resources*, SAE 2001-01-2650, 2001.

[20] Walton, J. D., Filman, R. E., Korsmeyer, D. J., *The Evolution of the DARWIN System*, Association for Computing Machinery Symposium on Applied Computing, Como, Italy, March 2000.

[21] Hillier, F. S., and Lieberman, G. J., *Introduction to Operations Research*, Holden-Day Inc., San Francisco, CA, 1980.