A Simulation-Based System Design Tool for Avionic Fiber-Optical Networks

Sven Jäger, Armin Zimmermann, and Ralph Maschotta
System and Software Engineering Group
Computer Science and Automation Department
Ilmenau University of Technology
Ilmenau, Germany
Contact: see http://www.tu-ilmenau.de/sse/

***Abstract*—Model-based analysis and validation using simulation is a helpful tool in the engineering of complex systems. This paper presents a tool chain for the model-based architectural design of avionic fiber-optic networks. A recently proposed framework for simulation-based domain-specific tools is the basis for the development. It supports a model-based design workflow and offers a new 3D graphical user interface for location-based configuration and result visualization of the underlying simulation tool. The benefits of the tool are validated with an application example, in which different topologies for avionic fiber-optical networks are evaluated and compared.**

Keywords—System Design, Simulation, Tool Chain, 3D User Interface, Avionics, Fiber-Optical Communication Networks

I. Introduction

Model-based systems engineering has shown its benefits in academic and industrial projects, and is thus widely accepted for the design of complex systems. Among the reasons are a reduction of costly failure corrections in late development stages caused by defective system specification documents and an increased overall system quality through early validation of design decisions.

However, as general-purpose modeling tools become more complex, there is an increasing amount of system-specific knowledge in a design project involved. Domain experts usually do not need all aspects and functional diversity of an underlying general-purpose modeling and simulation environment for their actual work. Thus, a simulation-based system design and validation software tool is often needed for the actual system designers. This partitioning of responsibilities also enables system designers to concentrate on their task without the risk to introduce errors in the underlying system model of given constraints.

Many components of such a simulation-based application can be generalized, as they are typically involved in this type of programs. Examples include modeling user interfaces, simulation modules, result visualization, common data storage in a data base, etc. A unifying framework enabling the rapid development of extensible and reusable simulation-based applications has been proposed for this task recently [1]. It supports an agile, iterative, evolutionary, and architecture-centric software development process. This paper presents results on a new application domain (fiber-optical avionic networks) and its integration in the framework, the underlying tool chain, as well as an additional 3D graphical tool for model configuration and result presentation. The use of the tool is validated with a design example of nontrivial size.

Airlines and thus also aircraft manufacturers have a growing interest in environmentally-friendly aircrafts, which are equipped with in-flight entertainment systems. Other innovative features of aircraft design include structural health monitoring and adaptive maintenance. These example applications lead to growing requirements on communication bandwidth and reliability, while power consumption and weight should be kept at a minimum. The present functional decomposition and chapter-based aircraft design as enforced by the Air Transport Association (ATA) leads to a set of independent communication networks. While this eases safety certification processes, it is a very inefficient resource use compared to a jointly planned, integrated on-board communication network. The up-scaling of traditional copper networks is becoming cost-ineffective, since the increased weight leads to higher fuel consumption. The amount of bandwidth of merged communication streams, as well as low weight and independence of electromagnetic interference, makes fiber-optic technology [2] a promising alternative, which is already used in parts of some aircraft designs [3].

The design of an integrated communication network has to take into account all requirements of several design chapters which are independently considered so far. The design task resembles a global optimization of several subsystems and is obviously a hard task, which may benefit greatly from a model-based engineering approach. A joint model of resources and requirements helps designers to base their local design decisions on their effect on the global non-functional requirements [4]. In [5], the benefits of a system design view on photonic avionic networks aiming at several non-functional properties are discussed. The authors of [6] survey candidate photonic network architectures suitable for embedded avionics applications, and propose an optical LAN-like bus structure.

Steps towards a necessary design process and tools for it have been taken in the recently finished EU-funded project DAPHNE[1] (Developing Aircraft PHotonic NEtworks). Optical network components such as splitter/coupler devices, fiber cable and multiplexer/demultiplexer for Wavelength Division

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[1] c.f. `http://www.fp7daphne.eu/`

Multiplexing (WDM) were developed and simulated. The main advantage of a MBE approach is to simulate and evaluate a system at early design stages, and to avoid integration issues caused by incomplete specifications. It differs from previous work, which has been focused mainly on physical- and lower-level models [7], [8], [9], by analyzing the network architecture [10], [11].

Our earlier work presented in [11] covered a methodology and software tool capable of an automatic model-based bandwidth planning for an integrated fiber-optical network. This is based on real-life subsystem requirements, and the tool then uses the derived link topology to compute end-to-end reliability figures (based on fault trees) to be compared with avionic design assurance levels (DAL). Moreover, metrics such as delays, weight and cost of the integrated network are computed. The underlying model describes functional blocks, links, and their discrete-event behavior with the multi-formalism simulation tool MLDesigner [12], [13]. However, as many of the input data and computed results are tightly connected to the physical location of system elements inside the aircraft body, the pure amount of data requires a graphical 3D view for modelers and system designers to work with the tool efficiently.

The contribution of this paper includes a graphical domain-specific tool that has been developed for this task recently. Configuration parameters of the underlying simulation model can be selected and results visualized. Different aspects of one model can thus be described and analyzed in their own, very different views, which is beneficial for system designers and modelers. Moreover, an integrated tool chain for the involved tools is introduced based on a framework of simulation-based system design tools [1]. The advantage of such a tool environment and model-based workflow is shown with an example in avionic fiber-optical network design.

The paper is structured as follows. The architecture of the used software framework is recapitulated in Section II, including a description of the new 3D visualization component in Section II-A and a design workflow supporting an integrated model-based design methodology (Section II-B). Section III introduces an application example, in which different topologies for avionic fiber-optical networks are modeled, evaluated and compared. Finally, concluding remarks are given.

II. A Simulation-Based System Design Tool

It has been motivated in the introduction, why domain-specific implementations of *simulation-based applications* (i.e., software tools that support a model-based design via behavioral models and performance evaluation) are beneficial for system designers, who are often not experts in modeling and are concentrating on system-level decisions and structural or parameter optimization of a planned system. To solve this issue, it is important to hide the complexity of the simulation tool and the system model from this user group. However, an application (and proper user interface), which gives access to the parameters and checks their complex dependencies, is necessary to select design options. Such a tool should also control the simulation or other performance evaluation algorithm, as well as analyze and present the results to the user in a domain-specific way.

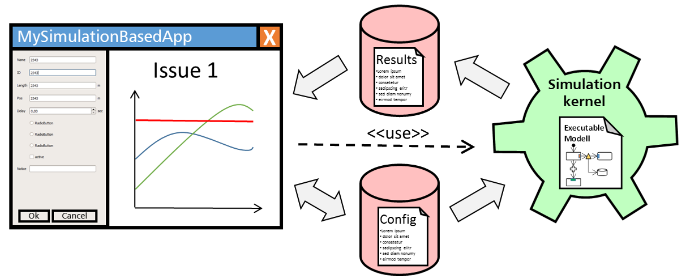

Fig. 1. Proposed general structure of simulation-based applications

To ease the development of such tools, a generic framework for this class of programs has been proposed recently [1]. Figure 1 depicts the general structure of such a simulation-based system design tool that we propose for such a situation. It can be integrated in an engineering design process for validating configurations. An underlying modeling and simulation environment is wrapped by the application and controlled using a simulation control interface. This interface needs at least capabilities to start and stop the simulation, and to access model parameters and numerical results. The system model is used by the underlying modeling and simulation environment and should be already developed before. Configuration data and results of the simulations are stored in a specific database. The contents of the configuration database can be altered and validated by the simulation-based application. During a performance analysis, the simulation kernel reads the configuration, and writes the simulation results into the result database afterwards. Finally, the result database is read by the simulation-based application to analyze results, compile visualizations, and generate simulation reports.

A. 3D Visualization Plugin

A special requirement for the application area that has been chosen here, i.e., fiber-optic network design in avionics, is the large amount of system design aspects that are based on or depend on the resource location inside the aircraft fuselage. The system designer should concentrate on high-level architectural decisions, and not be bothered with details which can be automated with rules, such as the individual path planning

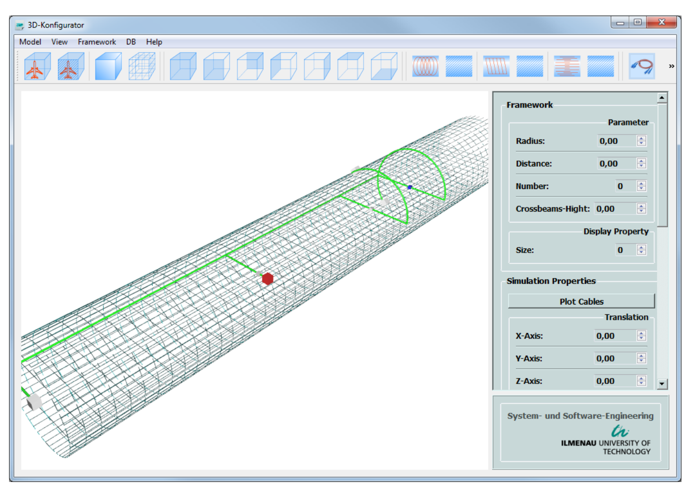

Fig. 2. Sample screen shot of the 3D visualization

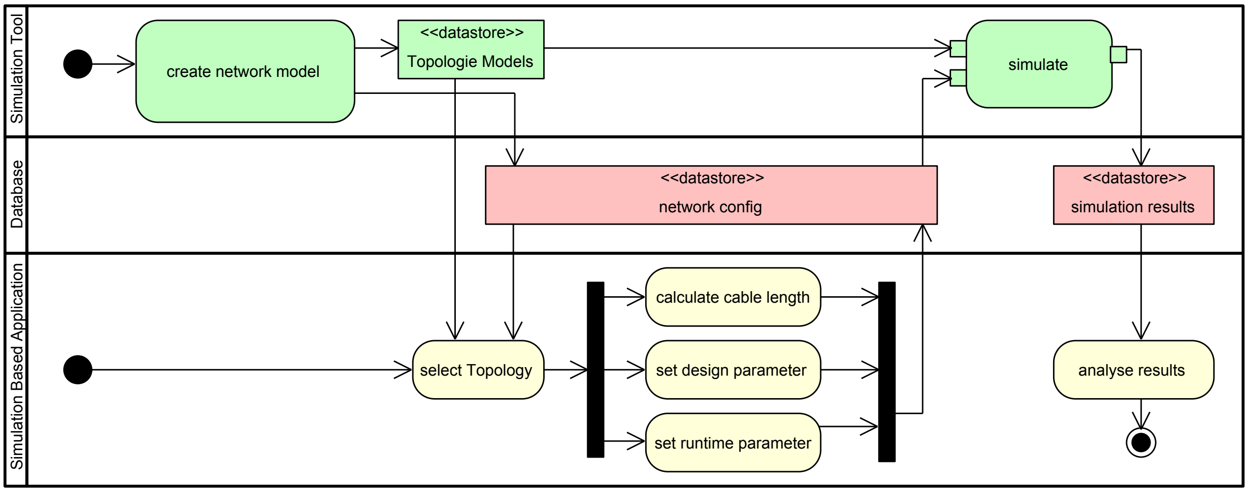

Fig. 3. Proposed workflow and corresponding parts of the tool chain (UML activity diagram)

of node-to-node links in the aircraft's hull. Moreover, results and unresolved requirements should be visualized adequately and not just as a list of text. For this reason a plugin to our generic framework was developed, which visualizes the three-dimensional positions of components and cables in the network. Figure 2 shows a screen shot.

Beside the visualization, the plugin calculates routes and lengths of the fiber-optic cables of the network in 3D space. This is however an approximation, as it does not take into account detailed CAD data and issues such as bundling and corner bending. It reads the position of the components of the network and the topology of the network from the database and generates a 3D model. Moreover, it calculates optimal routes and lengths of cables by using a constraint solver.

Our routing constraint is based on modeling the fuselage as a cylinder which is intersected by a plane (the cabin floor). Routing and placement for cables and components are only allowed on the cylinder or on the plane. There are three possible routing directions on the 3D framework. On the cylinder, routing is allowed on a rectangular grid defined by the so-called stringers and frames that stabilize the fuselage's structure, while cables can only be routed in the radial direction of the cylinder at floor level. This routing constraint is only an approximation of a future fiber-optic cabin hull. By moving the routing code out of the model it is possible to integrate and compare more complex constraints for the cable routing. The calculated cable length of each cable is stored in the database and is used to increase the accuracy of the simulation. In addition to that, it is possible to plot results on the 3D model after an analysis run in the simulation tool.

B. System Design Workflow and Simulation Tool

The tool architecture and the data/control flow for our simulation-based system design tool sketched in Figure 1 is described in more detail in this section. The components of the architecture and the data flow between them (which enforces a certain workflow) is presented in the activity diagram in Figure 3.

The architecture consists of three parts:

1) The simulation tool MLDesigner [12], [13], [14], a multi-domain simulator, in which the model is built and simulated; it allows the modeling of hierarchical models by using block diagrams.
2) The database which stores configuration and results (c.f. Section II-C); and
3) the 3D configuration tool which calculates routes and length of cables in 3D space, that has been explained above in Section II-A.

Modeling a network system requires adaptable building blocks, which are based on the functional network layer. A domain-specific MLDesigner library for fiber-optical networks has been created in the DAPHNE project [11]. The library provides essential abstract building blocks for the most common optical components like cables, switches, splitters, connectors and transceivers. The library supports modeling and designing fiber-optic network structures and layouts by using component and transmission medium models. Before a later simulation, parameters of the building blocks are set to specific properties of real hardware components based on configuration information. The resulting network models allow an evaluation of cost, weight, energy consumption, network load, latency and packet loss. It can be used to calculate and estimate the network's relevant non-functional parameters to decide which architecture or topology is the best one.

The workflow starts with the construction of the network structure in MLDesigner by using the abstract building blocks in the discrete event domain. To evaluate different topologies, each topology has to be modeled in its own MLDesigner model. The building blocks are connected to each other, and the user has to set design parameters such as the physical position of the components during the construction of the network model. When the specification is finished, the network topology is analyzed by the tool and end-to-end network routes are detected and planned for the necessary bandwidth as well as saved to the database.

After creating the structure of the network, the parameters of the components and topology models can be accessed by the user via the simulation-based application. The parameterization of the network model requires several steps. Consequently, the simulation progress is divided in three phases in order to control the sequence and to prevent incorrect operations.

After calculating the length and routes of the fiber-optic cables, the user sets specific properties for the components in the network. The GUI dialog for an example configuration is shown in Figure 4 as an example of application-level parameter setting for the user.

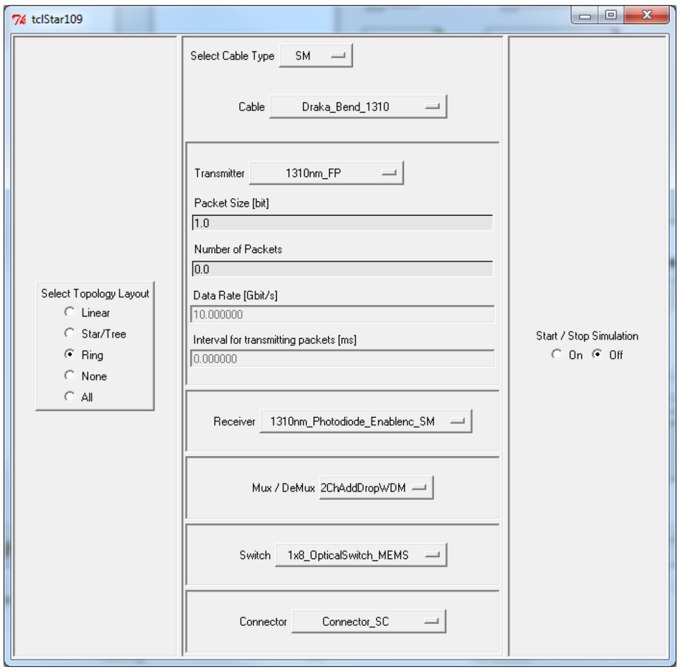

Fig. 4. Dialog for runtime parameter setting of fiber-optic network models

The simulation tool executes data transmissions during the construction of the network model. Messages are generated by a triggered stochastic event. Each transmitter component is triggered in a particular interval and creates packets. On the receiver side, the message is checked against destination and optical power level. If the signal strength is not in the range of the specification, the receiver drops the packet and creates a record in the data base. The latency is calculated for each end-to-end connection and saved in the database.

The last simulation step prepares simulation results to evaluate the designed network model. During simulation, MLDesigner continuously exchanges data with the data base. The latter stores simulation results including value, timestamp and result ID for each event. Topologies can be studied in terms of cost, weight and energy consumption.

The analysis of the simulation results is done in the simulation-based application, which provides several possibilities including significant events plotted versus time, or the influence of a design parameter on a performance result in a graphical manner. It allows evaluating the results of a single topology or to compare them after an experiment including several topology models.

C. Data Base Integration

The data base (center of Figure 1) is the central point for data exchange between simulation-based application and simulation tool with the system model.

Apart from the model configuration and simulation results, it can be used to store domain-specific data. In our example application, for instance, this includes hardware specifications of possible links and nodes (splitters, couplers etc.) taken from existing products. The specifications are used to set attribute values of abstract building blocks from the domain-specific MLDesigner library with real parameter numbers. MYSQL is used as the data base management system (DBMS) of our tool chain.

The data base may also serve in the future as a central repository for data exchange with other designers, and to integrate the capabilities of the new tool into existing design systems in the future.

III. An Application Example

Avionic network architecture design strongly depends on requirements from aircraft manufacturers and regulatory bodies, and affects the economic efficiency of aircrafts. An integration of different network systems requires high bandwidth for applications such as in-flight entertainment (IFE). Another aspect which is important to aircraft manufactures and airlines is the reduction of cost and weight as well as energy consumption. The network topology and architecture has a major impact on these properties.

The application example considers two different topologies for a fiber-optic network supporting the in-flight entertainment (IFE) system in an aircraft environment. The two topologies are described first, before they are analyzed and results compared with the proposed tool. For simplicity, we choose a simple linear/bus topology and a bidirectional ring.

The system setup which does not depend on the actual network solution and thus does not have to be optimized is modeled first, as it stay constant for any actual network architecture. We call this the null/zero topology model, which is depicted in Figure 5.

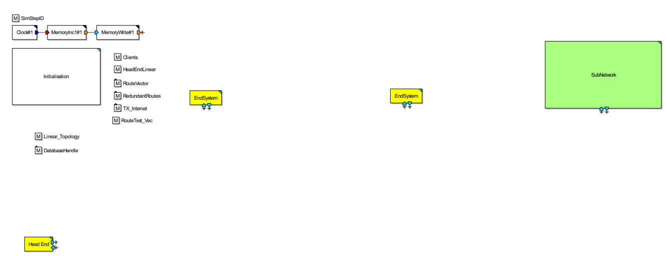

Fig. 5. Basic MLDesigner model with IFE server and three consumers (requirements model without a network topology)

It consists of a head-end server in front of the cabin (left side) and three consumer nodes for demonstration simplicity, one in the middle and two at the end of the cabin. For each topology, the positions and properties of these components remain the same. It can be imagined as constraints or part of the functional requirements that are given.

A. Linear Topology

The structure of the linear topology model in MLDesigner is shown in Figure 6.

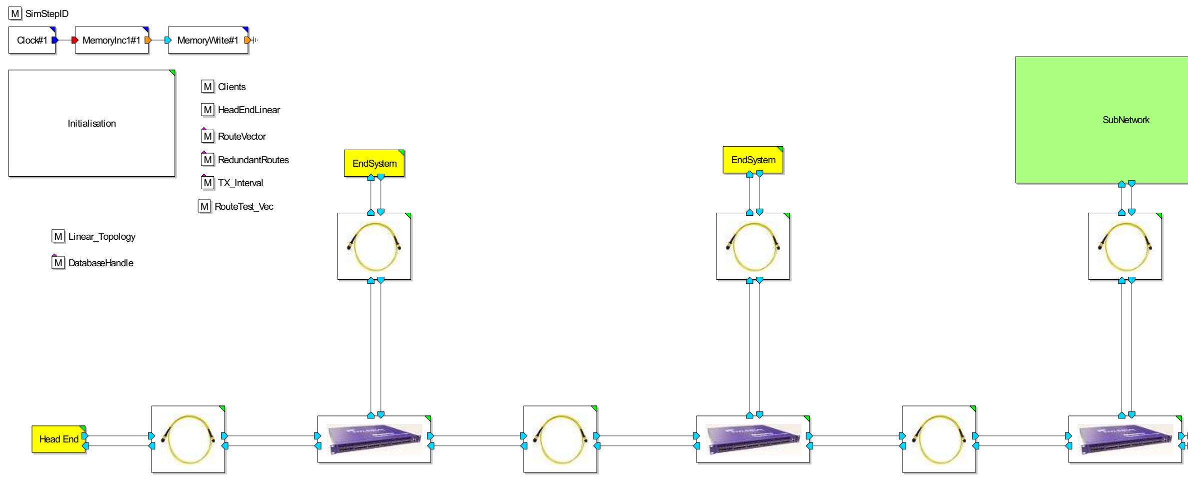

Fig. 6. Fiber-optic network model (linear topology) in MLDesinger

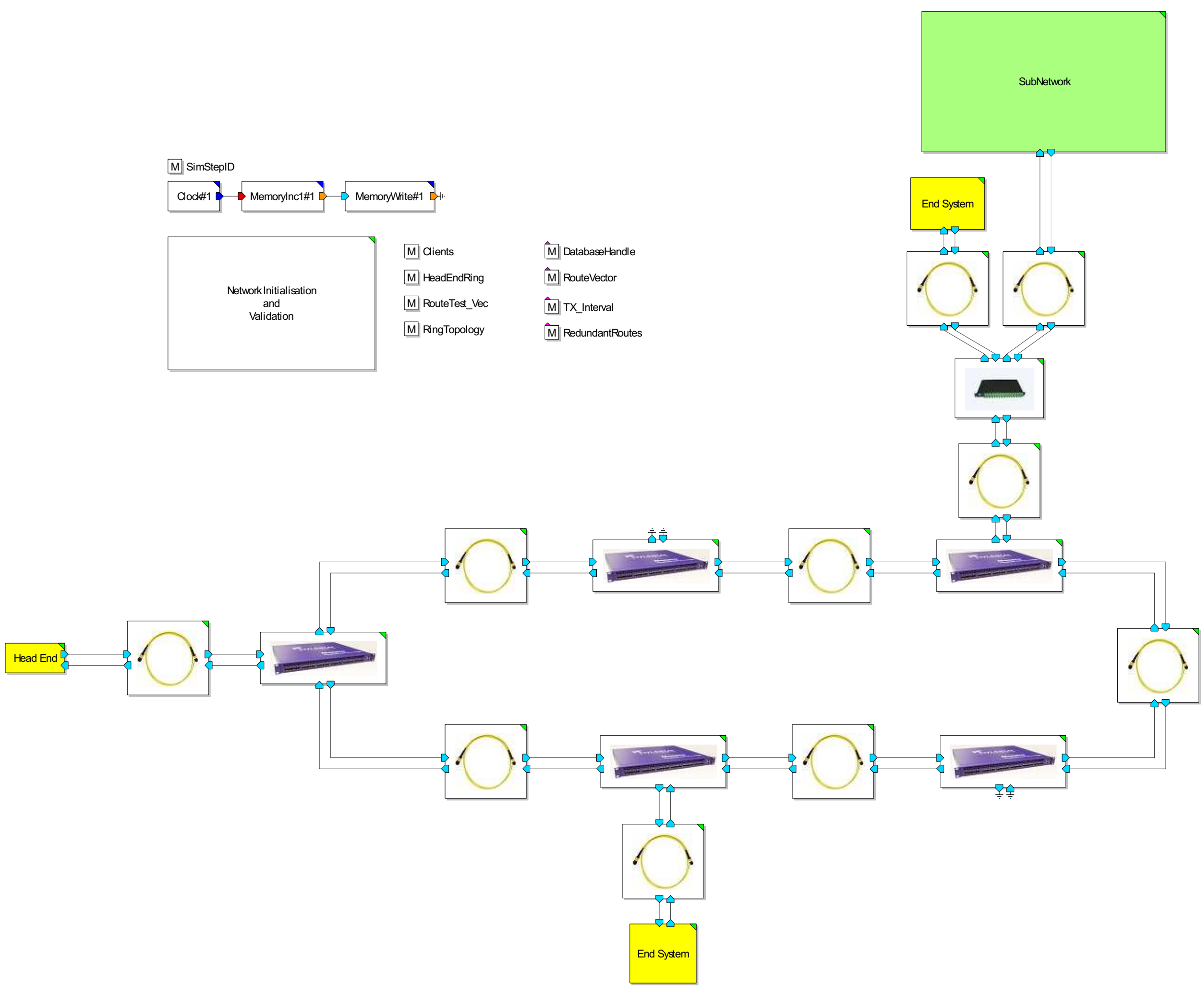

Fig. 7. Fiber-optic network model (ring topology) in MLDesinger

It consists of one bidirectional communication line with the IFE server at the head of the cable. Three optical switches are used as ”‘break out”’s for the passenger communication signal connections.

B. Ring Topology

The structure of the ring topology model shows Figure 7.

The composition of the network components and cables build a ring with break-outs for passengers and IFE server. The topology is a bidirectional ring in which packets can flow in both directions along the ring. The components are arranged in a symmetric way.

C. Configuration

The configuration of the model, i.e., setting of system-level parameters, is done in our simulation-based application. Therefore a domain-specific input window has been implemented as shown in Figure 4. For our example, each topology uses the same specification for the base components, making their attributes independent of the chosen architecture. The parameters are listed in Table I.

TABLE I. CONFIGURATION OF THE COMPONENTS

parameter	component name
cable type	single mode
wavelength	1310 nm
cable	Draka Bend 1310nm
transmitter	1310nm FP
receiver	1310nm Photodiode Enablenc SM
switch	1x2 Optical Switch
connector	Connector KC

Beside the configuration of the network components, computing the routing of the cables is another important task of the simulation-based application. The rule-based constraint solver mentioned earlier in the paper is used for the planning of cable routes in the three-dimensional model of the cylindrical aircraft fuselage and floor.

The results are presented in Figure 8 and Figure 9.

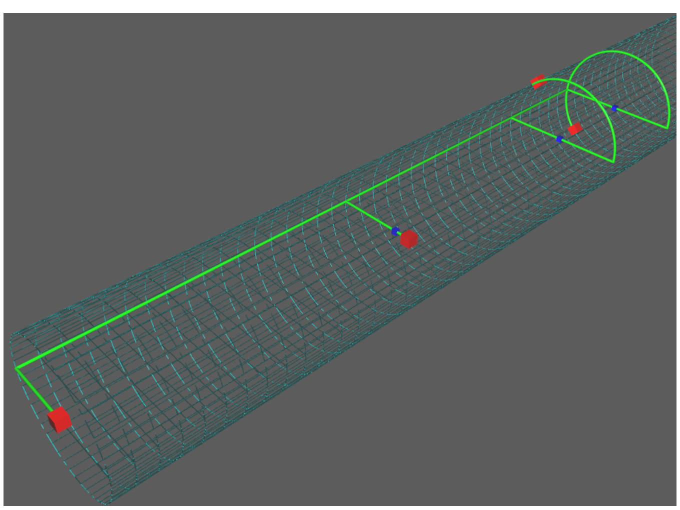

Fig. 8. 3D view of the linear network topology in the configuration tool

For the linear topology the constraint solver routes the cable on one side of the cabin. The red components are the transceivers of IFE server and consumers, while blue components correspond to switches. Green lines represent routes of the fiber-optic cables. For the ring topology, the solver routes the cables along both sides of the cabin.

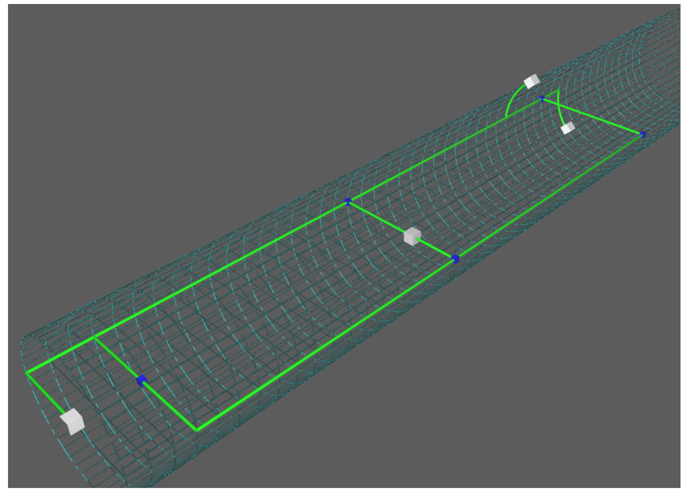

Fig. 9. 3D view of ring topology links in the configuration tool

After the configuration, the simulation-based application starts the underlying MLDesigner simulation for each topology, to analyze the non-functional properties of interest. During the simulation, intermediate results are saved in the data base for a later offline analysis.

D. Results

The results for cost, weight and energy consumption of the components in the sample network for each topology are listed in Table II.

TABLE II. RESULTS FOR THE TOPOLOGIES

parameter	ring	linear
weight	20.3 kg	12.5 kg
cost	249.60 €	160.00 €
energy	1.154 W	0.694 W

Besides the accumulated results for cost, weight and energy consumption it is possible to analyze performance parameters such as the packet latency over time for end-to-end connections. This is shown in Figure 10 for the linear toplology and Figure 11 for the ring topology, and allows to check for bursts, transient behavior etc. in addition to standard properties such as the mean or maximum value.

The plots are showing the overall end-to-end latency. It is also possible to analyze the latency for each component individually. Moreover, bandwidth utilization per link hop (load) and packet loss in each component can be estimated. With these results it is possible to base decisions about which topology to choose on actual behavioral models and analyses.

This small example shows how our tool chain can be used to support the design process for fiber-optical networks by using individual models for different topologies, and a simulation-based application to configure, simulate and analyze the model.

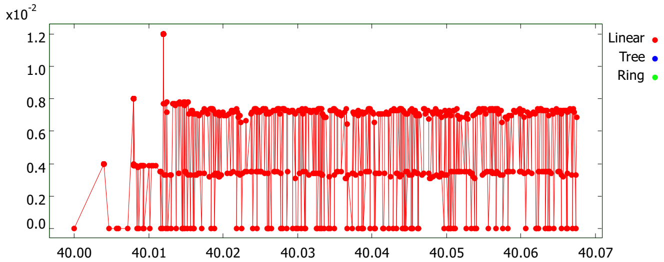

Fig. 10. Latency for the linear topology

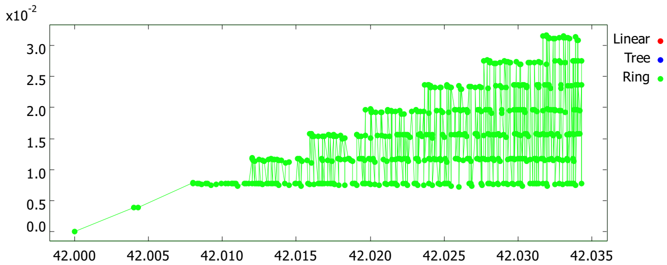

Fig. 11. Latency for the ring topology

IV. Conclusion

The paper presented an integrated tool chain for the model-based design of avionic fiber-optic networks. Different network topologies and local design decisions can thus be semi-automatically planned and their effect on the overall system performance, reliability as well as other non-functional properties evaluated in an efficient way.

Its architecture is based on a recently proposed framework for domain-specific simulation-based tools, and serves as an application example to prove its benefits. An integrated tool chain that hides the inner details from the user is presented, that supports a model-based design workflow. The underlying functional block and discrete-event based simulation model in the multi-formalism tool MLDesigner has been extended by a 3D user interface to ease configuration parameter editing as well as result visualization of the underlying simulation model.

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