Model-Based Design and Evaluation of Fault-Tolerant Fibre-Optical Networks for Avionics

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Abstract: Aircrafts need to provide and support a certain number of systems and functions today, in order to make the flight more comfortable and to avoid information overload for pilot and crew. Entertainment services, like HD video streaming as well as in-flight internet access or television are important for airlines to position themselves in the market. As a result for aircraft manufacturers, the demand of entertainment systems, improved flight controls, and monitoring systems is increasing steadily. On the other hand, adding more and more independent communication systems leads to higher cost and weight. An integration of some links would be beneficial. Higher bandwidth and data rates are required to integrate the increasing number of systems and functions. The existing avionic networks, which are mostly based on copper wiring, are not able to meet future bandwidth requirements. Therefore new network architectures are necessary to control the increasing information flow inside of an aircraft. Hence, fibre optics becomes progressively important to aviation, to enable the installation of new avionic systems in the future.
Avionic network architectures based on optical components need thus to be developed, tested and evaluated. To study fibre optic technologies within the scope of aviation, Model Based Engineering (MBE) is an essential tool. The objective of the paper is to show how optical network architectures are being designed for reliability and evaluated based on a functional layer modelling approach, by using the simulation tool MLDesigner. We report on intermediate results from the ongoing EU-funded project DAPHNE.
As a result, network architectures and optical components can be evaluated against their reliability requirements. A selection of different network design options are generated and analysed.

Keywords: Avionic networks, fibre optics, reliability evaluation, MLDesigner.

1. INTRODUCTION

Aircraft manufacturers and airlines have a growing interest in innovative and environmentally friendly aircrafts, equipped with latest entertainment and in-flight systems, to strengthen and improve their competitiveness in the market. This competitive situation pushes current aircrafts to face a high number of steadily increasing requirements, which seek to increase passengers' comfort, flight-crew awareness, and aircraft performance. Present Air Transport Association (ATA) chapter based design leads to a set of independent communication networks. However, fibre optics provides new ways for integrating systems, thus making way for integrated networks. The growing complexity of avionic systems leads to an increased flow of data across the aircraft, which requires a performance that traditional copper wiring networks will soon be unable to cope with, due to their physical/performance characteristics. The up-scaling of traditional copper networks is becoming cost-ineffective, since the increased weight leads to higher fuel consumption. As a result, fibre optic networks emerge as an interesting lightweight solution which offers a higher bandwidth and consumes less space. A combination of photonics network structures with existing electronic control units is promising in avionics as well as it is for other application areas [1].

To examine and validate new photonic network architectures, the Model Based Systems Engineering (MBSE, [2]) approach is necessary for today's complex avionic system design [3]. In this paper, MBSE is done by using MLDesigner, a mission level design tool which is used to model and simulate complex system behaviour. As part of the EU-funded project DAPHNE (Developing Aircraft PHotonic

NEtworks [4]), optical network components such as splitter/coupler devices, fibre cable and multiplexer/demultiplexer for Wavelength Division 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.

An introductory overview of model-based system engineering and simulation in avionics can be found in [3]. In [5], the benefits of a system design view on photonic avionic networks aiming at several non-functional properties are discussed. Optical network design for avionics has to consider several layers of detail. This paper aims at a network topology view and subsumes the effects of lower level elements. The authors of [6] survey candidate photonic network architectures suitable for embedded avionics applications, and propose an optical LAN-like bus structure. A three-layered network structure based on a ring optical network topology is proposed in the DAPHNE context in [7]. Signal-level modeling and simulation has been proposed with the Photonic Transmission Design Suite [8]. A physical-layer model for on-chip optical communication is presented in [9]. Modeling and simulation for an integrated avionics (non-photonic) AFDX network is presented in [10].

Node, link and module failure properties are important input parameters for a model-based engineering approach to reliability evaluation [11]. An overview of physical-level influences and measurement setups is given in [12]. For the purposes of our work, reliability values for photonic components are derived by partners responsible for hardware elements in the DAPHNE project and based on prediction methods [13, 14].

A software tool capable of modelling and evaluating complex systems is a necessary prerequisite for model-based design. A library of domain-specific modules is advantageous, as it makes the modelling process more efficient. In the ongoing DAPHNE project (and the paper), the software tool MLDesigner [15, 16, 17] is used, and its existing photonic network library is undergoing a major update. The tool has been successfully used in other avionics applications such as maintenance logistics [18]. There are many tools for model-based reliability evaluation available, e.g., [19].

The contribution of the paper is to show how techniques and tools of model-based engineering can be used to derive critical non-functional properties of a planned system. Reliability measures can be automatically computed using models of photonic networks in avionics. This is done using the topology generated during a design-space evaluation, and based on reliability predictions of photonic components.

The paper is structured as follows. Some of the photonic network topologies proposed in the DAPHNE project for avionics are briefly covered in Section 2. Section 3 describes the general approach of high-level photonic network modelling and software tool, and introduces an example model which is used in the following evaluation. Failure rates of photonic modules are derived, and the overall network reliability is computed for the example network in Section 4 based on these results. Finally, conclusions and acknowledgements are given.

2. NETWORK ARCHITECTURES

Avionic network architecture design strongly depends on requirements from aircraft manufacturers and regulatory bodies, and affects economic efficiency of aircrafts. An integration of different network systems requires high bandwidth for applications such as in-flight entertainment and radio-over-fibre, e.g., for offering WiFi access to passengers. Another aspect, which is important to aircraft manufactures and airlines, is the reduction of cost and weight as well as energy consumption.

The first step after specifying future anticipated requirements as a basis for planning is to develop a set of possible network architectures to be analysed. This process is also called *design-space exploration*. There are many aspects of a photonic architecture, including topology, the choice of single mode or multi mode fibre, passive or active network, or whether wavelength-division multiplexing (WDM) should be used. This list already shows the vast size of the design space, which cannot be searched completely for an optimal solution in a realistic time. Separation of communication links belonging to different levels of criticality (DO-178B/ED-12B design assurance levels, DAL) makes it easier to fulfil regulatory requirements. In photonics, WDM can be employed for this segregation, while simultaneously allowing its traditional application for bandwidth increase. Assuming the adoption of the WDM mechanism, we can concentrate on topology options for space restrictions here.

In an integrated network, the topology does not depend on the physical placement of end nodes as much as in characteristic ATA-based designs. An additional reason is the required flexibility or reconfigurability for different customers of the same aircraft type. Instead, the typical setup contains a head-end server located in the avionics bay (aircraft nose), and several remotes nodes that correspond to seat groups, switchboards, monitors, sensors, etc. A backbone network with links to the remote nodes is thus necessary. Depending on the direction of data transfer, we differ between upstream and downstream traffic. Different network topologies such as star, ring, mesh, or linear are possible for the network and studied based on models. Each topology is designed to support the functional requirements (logical links) and their required bandwidth and reliability. The resulting networks are compared w.r.t. the non-functional properties cost, weight, and energy consumption in the project. Four selected topologies that have been proposed in the DAPHNE project are briefly presented in the following. A sample model based on one of them is used in the later sections of the paper.

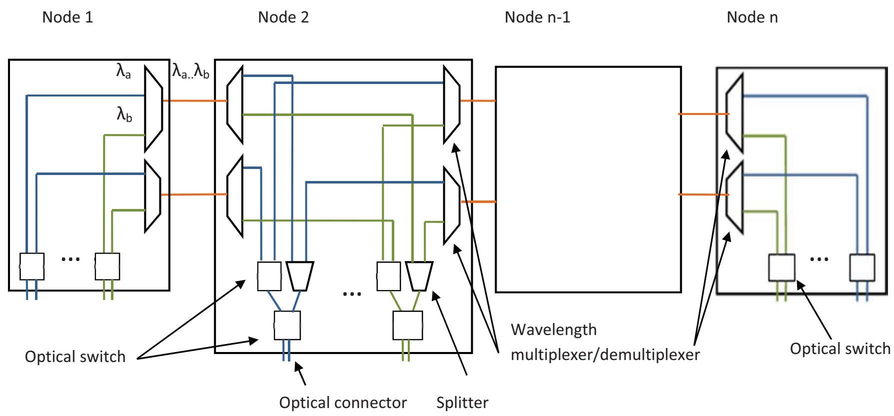

Figure 1: Linear Network Showing Node Components

The **DAPHNE linear topology** is illustrated in Figure 1. It arranges all linked nodes in a sequential manner. All nodes are connected to two half-duplex fibres, in which a combination of the nodes enables a full-duplex and bi-directional communication. Each node manages the same data flow, in contradiction to, e.g., a remote node in a star topology. As shown in Figure 1, at each non-terminating node, the end system selects one input fibre through its optical switch. The data is multiplexed with the outgoing data and sent to both output fibres. In a WDM-multiplexed network the nodes are also responsible for de-multiplexing the different channels, used by the end-systems, and multiplexing them back into the fibres they are connected to.

The proposed **DAPHNE star topology** is a simple 1:n-connection of a central node with remote nodes. Figure 2 depicts central and remote nodes for this setup. The maximum number of branches (i.e., remote nodes) is initially limited by the capacity of the central node's optical splitters. However, the maximum number of remote nodes can be scaled up through the application of intermediary splitters, installed between the central node and the remote nodes. As a result, received signal power on remote nodes becomes heterogeneous and upstream traffic multiplexing might require changes.

The central node contains an uplink and a downlink module. The downlink module is responsible for sending the data from the central node to the remote nodes (downstream traffic). Conversely, the uplink module is responsible for receiving the data from the remote modes (upstream traffic). Each remote node has two links towards the central node. One of the links is for downstream traffic and

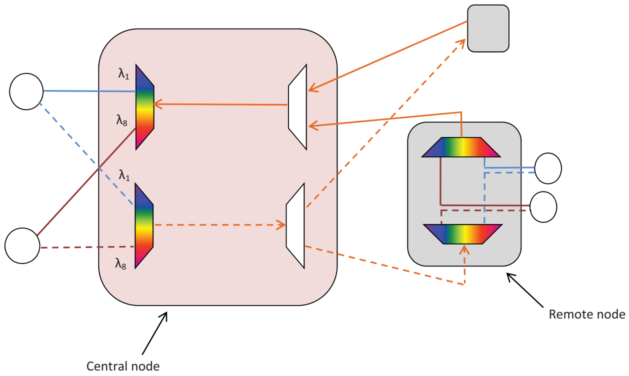

Figure 2: Star Network With Central and Remote Nodes

the other is for upstream traffic, as illustrated in Figure 2.

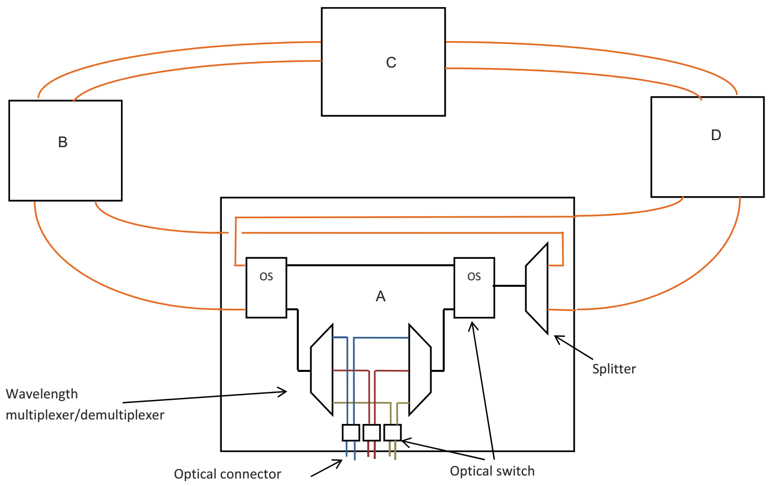

Figure 3: Ring Network Showing one of the Identical Nodes

A **DAPHNE ring topology**, presented in Figure 3, consists of a group of inter-connected nodes in the form of a ring. Each two nodes are either connected by one direct link (in fact, two dual-redundant fibres) or indirectly connected through one, or more, nodes and links. All nodes are similar in this setup.

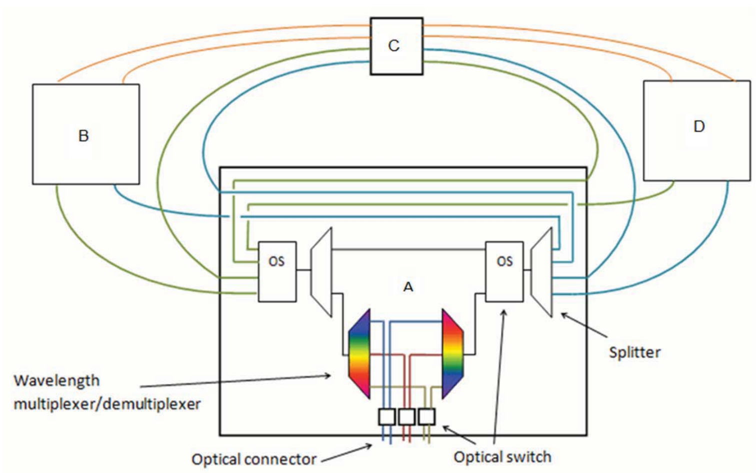

Figure 4: Mesh Network (4 Nodes) With Details of one Node

Finally, Figure 4 depicts the **DAPHNE mesh topology** design. Every node is connected to each other in a fully connected mesh. Technically it can be considered as an evolution of the ring topology, as each node may be connected to more than two nodes here. Increasing the number of connections enables higher data flow and increases fault tolerance. As a result, the design is more complex than a ring topology. Still, all nodes are similar and there is no central node.

Each of the proposed mesh nodes is composed by the following components: one 1x2 optical switch; eight 2x2 optical switches; one 1x4 optical switch; one wavelength mux and one wavelength demux; one 1x2 splitter; and one 1x4 splitter as sketched in the figure.

3. NETWORK MODELLING

Modelling of networks and their components for an architectural design is important in many applications. Depending on the design issues to be solved, different levels of detail are important. Physical-level models can answer questions regarding light dispersion and signal degradation by optical couplers. Packet-level models are helpful to design communication protocols. As we are considering the network architecture level, a higher level of abstraction is necessary. The design space of a network model strongly depends on the level of abstraction. A top-down approach is an appropriate way to perform architectural design, as it allows to enrich the model.

There are two kinds of network models being developed in this work package, a static network model and a dynamic, simplified packet-based, network model. The main issue is to calculate network load as well as cost, weight and energy consumption of all network components in comparison to copper based avionic networks. Reliability needs to be considered when modelling optical components (see Section 4).

We apply the integrated modelling and simulation environment MLDesigner [15, 17] in the project. The multi-formalism tool provides several modelling domains such as Discrete Event (DE), Finite State Machine (FSM), Dynamic Dataflow (DDF), and Synchronous Dataflow (SDF). The presented photonic network model is developed within the DE domain, which informally treats systems as a combination of functional blocks with input and output ports that are connected by links carrying events. Blocks can be hierarchically organized leading to a tree-like structure, where only the leaf nodes are predefined basic building blocks (which can be programmed if necessary). The previously existing photonic module library is improved and redesigned throughout the work. A set of basic optical components such as transceiver, multiplexer/demultiplexer, optical fibre cable and splitter/coupler devices has been designed and implemented. Afterwards, bandwidth allocation and simplified packet-based transmission was implemented as well as WDM functionality. For instance, a transceiver module creates, sends and receives data structures that model bandwidth allocation information in a static model, whereas a splitter module spreads the information of one optical cable to two or more.

All network- and simulator-relevant information like sink, source or data rate is stored in MLD data structures. Routing between source and sink of each data link is done automatically based on the modeled topology with a bandwidth allocation algorithm that iteratively assigns the shortest available path to logical links. The bandwidth load is calculated during the simulation for each connection link between the modules. Furthermore, parameters such as cost, weight and total number of installed optical components are computed and shown at the end of the simulation.

As an example, the DAPHNE mesh topology described in Section 2 has been modelled in MLDesigner (see Figure 5). The system consists of one head-end server, four DAPHNE mesh connector nodes (highlighted in yellow) and three end systems (A, B and C; marked in green). The mesh nodes receive and distribute the information through the network. Each module has input and output ports for each direction. Head-end server and end-systems have corresponding downlink and uplink connections, whereas the network nodes have input and output ports related to the switch layout inside the node. Furthermore, end systems as, well as the head-end server, contain transceiver models. The system sends information from the head-end server to the three end-systems via the optical backbone.

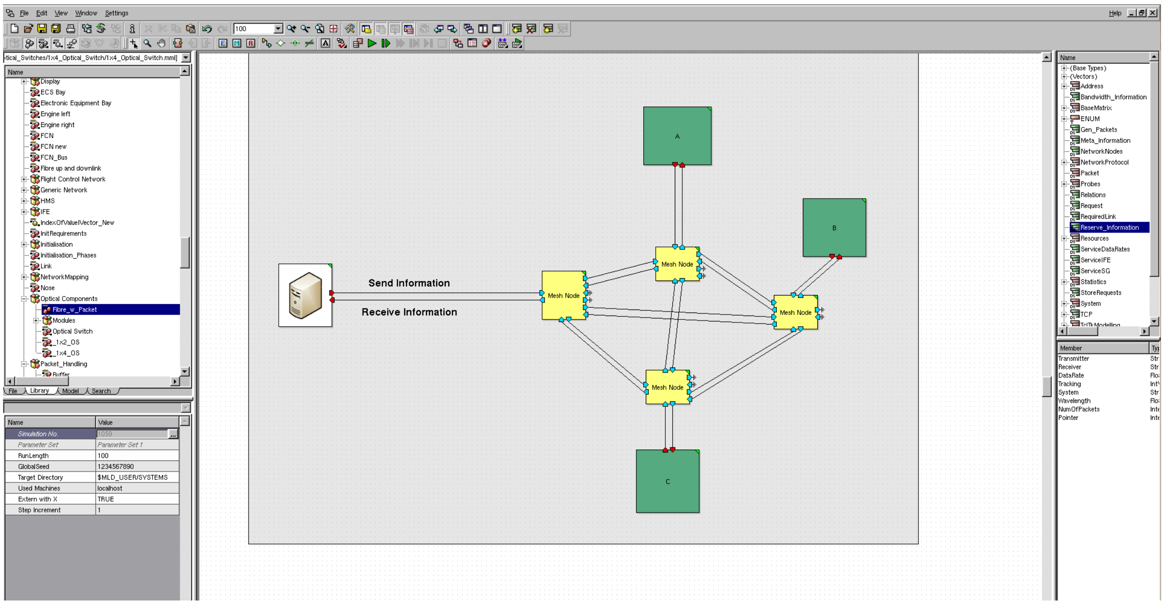

Figure 5: Screen Shot of MLDesigner With Sample Mesh Topology Network

A simple evaluation of the system provides the sample results shown in Table 3.

Weight in kg	Cost in Euro	Total Amount of Nodes
31.50	130.00	16

Table 1: System Layout Parameters

Another analysis based on the dynamic version of the model, which implements sending a certain number of packets through the network, shows the network load over time of an optical cable within the backbone connection in Figure 6.

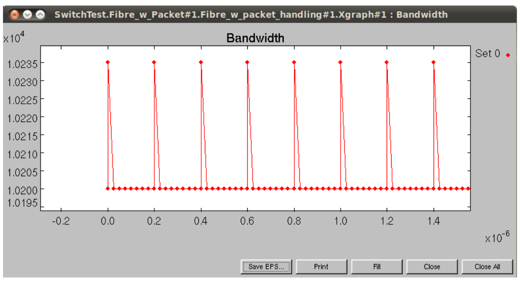

Figure 6: Used Bandwidth of Fibre Optic Cable Over Time

4. FAILURE MODELLING AND EVALUATION

The previous section gave a brief overview of the ongoing work on structural modelling of the network. Necessary input parameters for a further reliability evaluation are failure estimates for each photonic module (Section 4.1). Network reliability can then be computed from these numbers as well as the network topology by means of a fault tree, as demonstrated in Section 4.2 for the mesh network.

4.1. Failure Rates of Photonic Modules

Reliability predictions have long been an integral part of reliability programs, providing an estimate of field reliability before the networks are even built. This enables design options to be compared;

the feasibility of achieving reliability goals can be assessed, and initial sparing strategies can be formulated, e.g., via alternate design options. For this purpose, we have adopted an approach based on the MIL-HDBK-217 method [13] for assessing the reliability of photonic components and fibre. This method allows for an efficient evaluation of an avionic network design's reliability, based on its number of components and topology, environmental conditions (experienced in an avionic environment), manufacturing quality, and the components' individual failure rates.

The method MIL-HDBK-217 Photonics model form is [13]:

$$\lambda_P = \lambda_B \, \pi_E \, \pi_{OP} \, \pi_Q \tag{1}$$

where λ_P is the predicted failure rate (failures per million operating hours), λ_B equals the base failure rate (failures per million operating hours), π_E is an environment factor, π_{OP} equals the operating profile factor, and π_Q is a quality factor.

Each factor is computed taking as parameters the component reliability data extracted from several documentation such as Telcordia Test Reports, RIAC's Electronics Parts Reliability Data (EPRD [20]), Nonelectronic Parts Reliability Data (NPRD [21]), and RIAC's Failure Mode/Mechanism Distributions (FMD [22]) publications.

The network design chosen as an application example, among DAPHNE's proposals, for initial fault-tolerance studies was the Mesh Topology which suggests a high resilience. This network was sketched in Figure 4, and fully connects each node with every other one. The multitude of direct and indirect links that connect any two nodes in a mesh network makes it less probable, when compared to other topology alternatives, for any two nodes to become unable to communicate (at least indirectly). For two nodes to become unable to communicate between them, in a mesh topology, a series of node failures and link ruptures must coincide. The probability for this to occur is far inferior to the probability for two or more nodes to become unable to communicate in a linear topology due to a single link rupture, if one assumes that the probability for a node to fail, or a link to break, is the same on any topology. However, this suspected high fault-tolerance comes at the price of increased nodes and inter-node connection complexity, as it is characteristic for redundant solutions to fault tolerance. The trade-off between cost and reliability can then be decided using a model-based evaluation.

Based on the information specified above, failure rates for all parts of mesh network nodes (c.f. Section 2) are predicted with the MIL-HDBK-217 technique. The results are shown in Table 2.

Components	**Predicted failure rate**
Connector	9689.6
Switch	289.5
Splitter	2.8
Mux	282.7
Fiber	466.3
VCSEL of transceiver	106.1
Photodetector of transceiver	62.4

Table 2: Failure Rates for Each Component (Failures per 10^9 operating hours)

4.2. Fault Tree Derivation and Network Reliability

A Fault Tree Analysis (FTA) forms a basis for the analysis of a modular system in terms of reliability, availability and safety of a network design. It is used here to combine the topology and network routing information with the component reliability data to derive an overall measure of network reliability. An FTA is a deductive, top-down approach which provides a graphical representation of the relations between basic failures, using the failure-rate probability (λ) and a specific undesired system failure

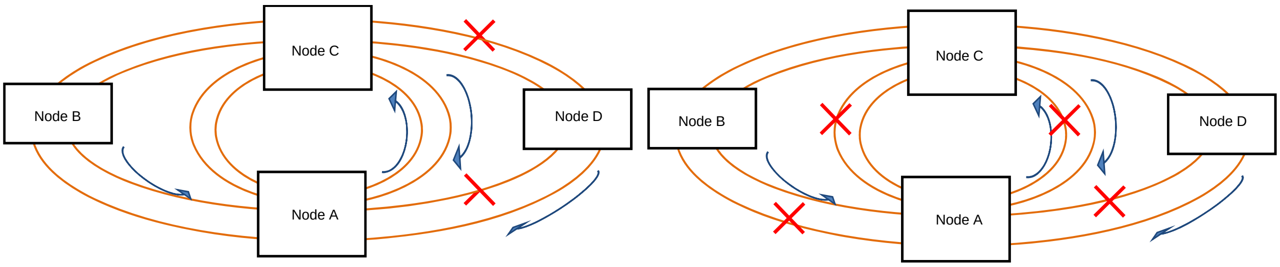

Figure 7: Examples of possible failures that cause the top event

(top event). For this study, the top event is a failure of the entire network, and includes methods for quantifying the risk of failure due to individual component errors.

Faults are considered as those events which prevent communication between one end-system, connected to node A, and another end-system, connected to node D in our example. An *end-system* is a component which extracts data from the optical network (e.g., an actuator), and/or injects data into the network (e.g., a radio altitude sensor). From the backbone photonic network point-of-view, the end-system is either a) a data-source, or b) a data-sink; both implemented as a transceiver. We assume that an end-system does not fail (it may fail but its failures are not accounted as photonic backbone network failures, hence they do not impact the photonic backbone's reliability). Furthermore, failures of a network component occur independent of wavelength, the amount of exchanged data, protocols and type of exchanged data. Physical-level issues such as wavelength channel crosstalk and inter-system interference are beyond the scope of this paper.

The design of a fault tree usually requires a manual analysis of a system or a failure mode and effects analysis. As a result of our topology models being described in a software tool which derives all possible routes via optical modules automatically, the fault tree can be directly derived from the model. The result will be a simply structured, but sometimes unnecessary verbose expression, which can be reduced with boolean rules. For our example, a subset of possible failure scenarios in terms or inter-node connections are depicted in Figure 7. Considering the predicted failure rate for each component, the failure scenarios and the assumptions above, it becomes possible to design the fault tree for the DAPHNE mesh topology, as illustrated in Figure 8.

The tree states that, for the top event (communication failure, illustrated by "F") to occur, a failure must occur in node A or in node D, or in the link (direct or indirect) between them. Considering that

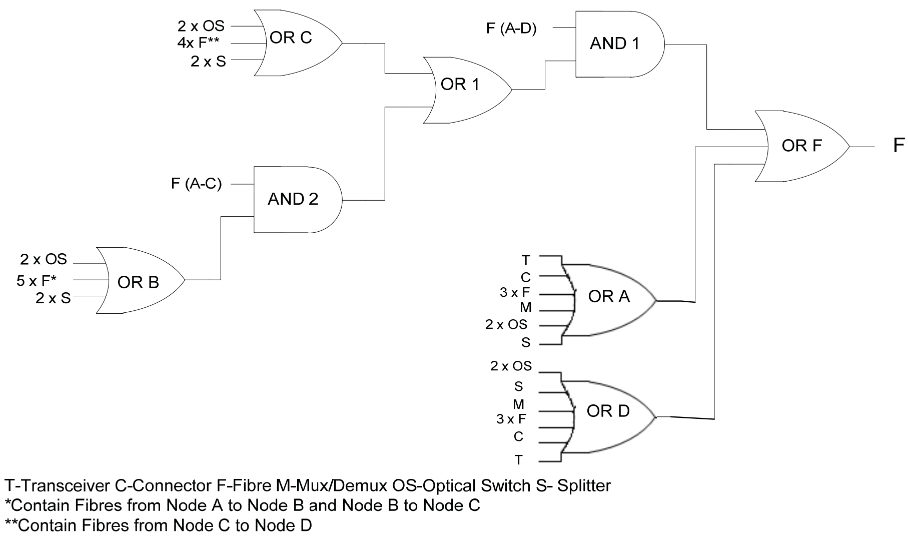

Figure 8: FTA for Mesh network

nodes A and D are connected through more than one link, their connection fails if all of their links fail, according to possible failure scenarios present in Figure 7. In terms of predicted failure rate for the top event, using the predicted failure for each component using the MIL-HDBK-217, is λ_P=27665.3 failures per 10^9 operating hours, which implies a Mean time to Failure (MTTF) of 36146 hours for this mesh topology example.

5. CONCLUSION

Integrated photonic networks have the potential of significant savings in weight and cost for airline manufacturers. However, complexity of such systems as well as critical reliability issues lead to severe risks in the design process. Techniques and software tools in model-based system engineering are a valuable help for this task. The paper presents intermediate results of the ongoing DAPHNE project, and shows how failure measures of photonic networks can be obtained from a topology model. A fault tree is derived, and connectivity reliability is then computed from it, based on a prediction of photonic module reliability. Furthermore, some photonic network architectures for avionics are proposed.

In addition to the static fault tree model and reliability measures presented here we plan to cover dynamic reliability aspects with our simlation model, such as possible network reconfigurations and their inherent trade-offs (reaction time, cost and weight of reconfiguration hardware, etc.). Another future task is to incorporate dynamic effects of the environment (temperature, vibration, etc. depending on flight cycles), which are characteristic for avionic applications. A sample model will be validated using the upcoming DAPHNE hardware demonstrator test bed.

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