Analysis and Design of Redundant Networks for Satellite Payloads

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This article discusses analysis and synthesis techniques for the design of redundant networks for satellite payloads. The proposed approach, based on the topological representation of the redundant network, has been implemented in a dedicated simulation software and successfully adopted for many satellite payloads manufactured by Alenia Spazio, a division of Finmeccanica and a leading supplier of space systems and hardware.

Introduction

In a satellite communications network, the satellites represent the nodal point, i.e., the mandatory point of passage for a group of simultaneous links.

The satellite consists of a *payload* and a *platform*. The payload includes all the equipment needed to receive the uplink signal and to transmit the downlink, after amplification and frequency shift. The platform consists of subsystems that permit the payload to operate, including mechanical structure, electric power supply, temperature control, attitude and orbit control, propulsion equipment, tracking, telemetry and command equipment.

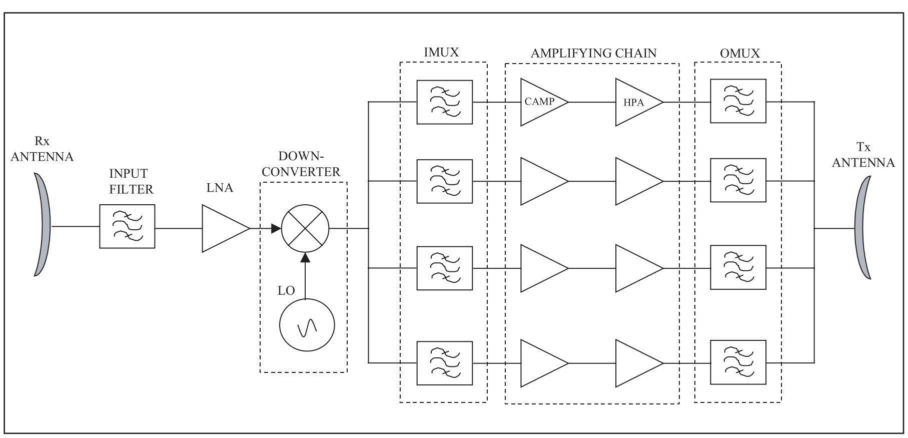
To ensure service with a specified availability, a sat-ellite communication payload exploits the redundancy of the most critical units. Because repair of failed components is not feasible, many functions are duplicated and complex switching matrices provide redundancy. As a result, all recent satellites have an increased design lifetime and increased reliability but are more complex in payload design.

This article provides an architectural overview of a transparent satellite payload; introduces the redundancy concept, placing emphasis on the transmitter section; deals with coaxial and waveguide switches behavioral modelization; offers an in-depth description of the proposed analysis and design approach; points out some implementation issues; presents a case study; and discusses issues relevant to the redundant network reliability analysis.

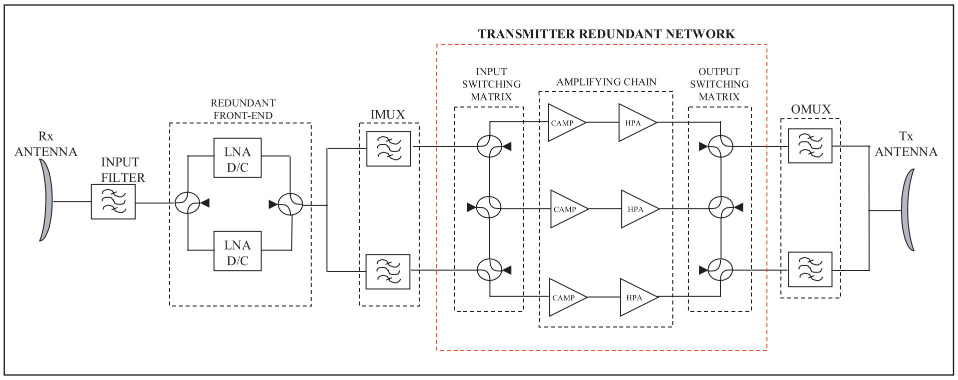
Satellite communication payload architecture

Figure 1 shows a simplified block diagram of a transparent satellite payload, i.e., in which no demodulation, regeneration or baseband processing occurs [1].

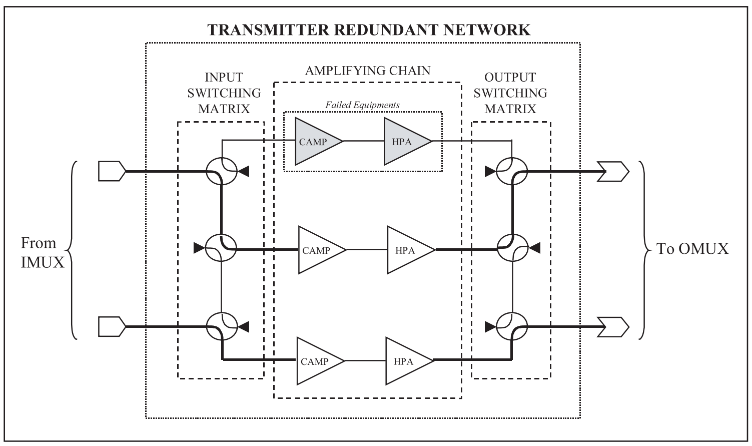
The transparent satellite payload contains the following building blocks:



▲ **Figure 1. Simplified block diagram of the transparent satellite payload.**



▲ **Figure 2. Simplified communication payload block diagram, including back-up equipment.**



▲ **Figure 3. Schematic showing 2/3 transmitter network redundancy management.**

- Receive (Rx) antenna
- input filter
- low-noise amplifier
- downconverter
- input multiplexer
- channel amplification
- output multiplexer
- Transmit (Tx) antenna

The Rx antenna receives the uplink signal transmitted by the earth stations of the satellite network. The input filter performs wide-band filtering of out-of-band interference. The low-noise amplifier (LNA) provides gain with minimal additive noise at the uplink frequeny. The downconverter performs a frequency conversion between the uplink and the downlink, to prevent interference between the received signal, at a few picowatts, and the transmitted signal, at a few hundred watts.

In the spacecraft, the power efficiency is maximized by driving the power amplifiers near saturation, where they behave nonlinearly and generate intermodulation products. To cope with the intermodulation noise, the uplink band is split into several subbands (repeater channels) by means of the input multiplexer (IMUX). A dedicated amplifying chain is used for each subband. Thus, intermodulation noise is decreased by reducing the number of carriers at the input of each power amplifier. Amplification of each channel uses a driver amplifier (CAMP), providing the signal level needed to drive the microwave power amplifier (MPA) stage. The latter may be implemented by employing either solid-state power amplifier (SSPA) technology or vacuum technology (traveling wave tube amplifier, or TWTA). The amplified signals are combined in the output multiplexer (OMUX) and fed to the Tx antenna for downlinking.

Redundancy

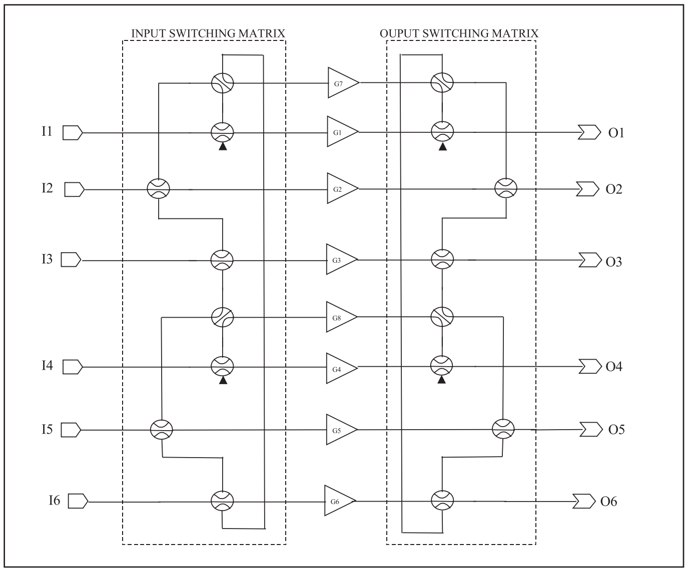
The satellite communication payload outlined in the block diagram shown in Figure 1 does not include back-up equipment. In this case, equipment failure may cause the loss of the mission (single point failure). In satellite systems, the communication payload includes spares of the most critical units to guarantee required reliability, reducing the chance of single point failures as much as possible.

The use of redundancy is generally limited to receiving and amplifying sections of the communication payload, as shown in Figure 2. Because their failure rate is very low, passive elements such as IMUX and OMUX are not backed up.

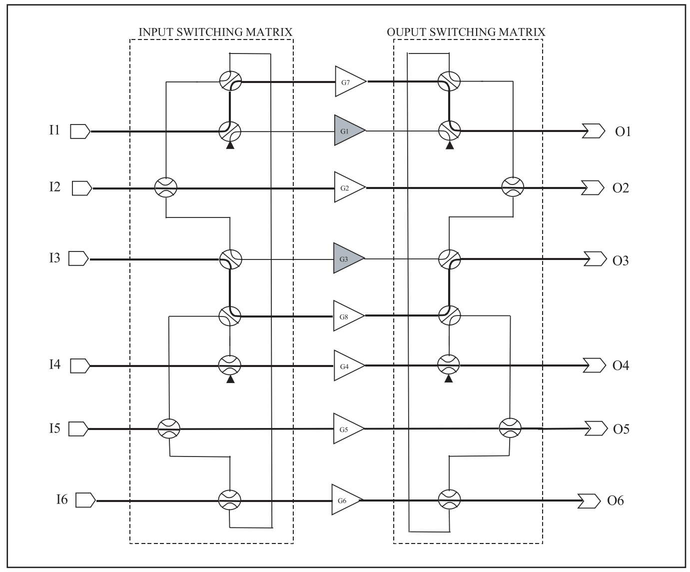
Units common to many of the communication channels, such as the LNA, the downconverter and the local oscillators, are usually duplicated with an identical back-up unit (one-half redundancy). A switch operated by telecommand selects the active unit, providing the proper routing of the signal.

Channel amplifying equipment redundancy is managed by switching matrices. Each channel at the output of the IMUX can be directed to the input of several amplifying chains by means of a set of interconnected multiposition switches (input switching matrix). The amplified signals are then routed to the relevant OMUX inputs by the output switching matrix, which is a mirror of its input counterpart.

For this article, the system consisting of the input switching matrix, the amplifying chain and the output switching matrix is called the transmitter redundant network or, simply, redundant network. For example, Figure 2 shows a 2/3 redundant network. The input switching matrix routes the signals available at the IMUX output to two of the three installed amplifying



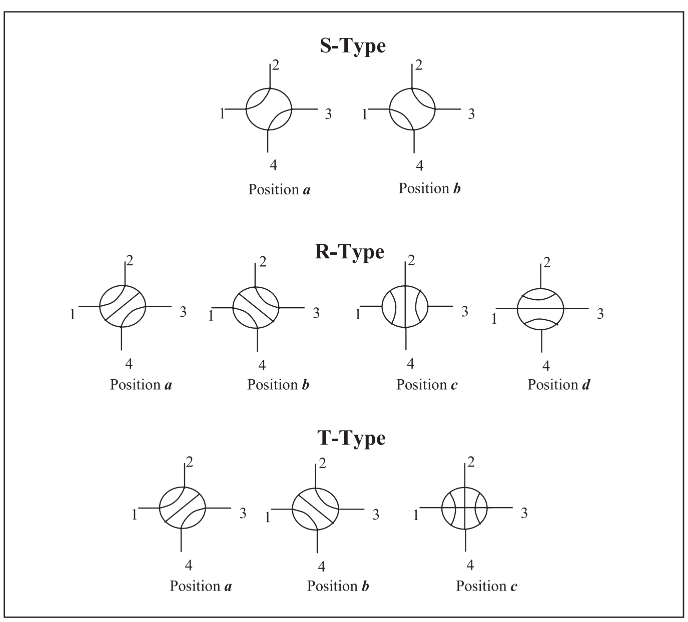
▲ **Figure 4. Schematic of a 6/8 redundant network showing nominal configuration.**



▲ **Figure 5. Schematic of a 6/8 Redundant network showing recovery of G1 and G3 failures.**

chains. The output switching matrix routes the signals from the two active chains to OMUX inputs. If one of the active amplifiers fails, the stand-by unit replaces it, as shown in Figure 3. A second failure results in the loss of one communication channel.

With an increase in the number of channels, the redundant network architecture becomes more complex. Consider, for example, the 6/8 redundant network shown in Figure 4. According to this layout, the input switching matrix has eight switches connected. Amplifiers G1 through G6 are the nominal equipment, and amplifiers G7 and G8 are the redundant equipment. If there are no failures, the six communication channels C1 through C6 are amplified by the relevant units, i.e., G1 through G6, as indicated in Figure 4.



▲ **Figure 6. Microwave switches.**

To illustrate redundant network operation, assume the simultaneous failure of amplifiers G1 and G3. In this case, the switching matrices are reconfigured with the switches in the recovery positions, as indicated in Figure 5, where the redundant equipment G7 and G8 replace the failed ones, G1 and G3, respectively.

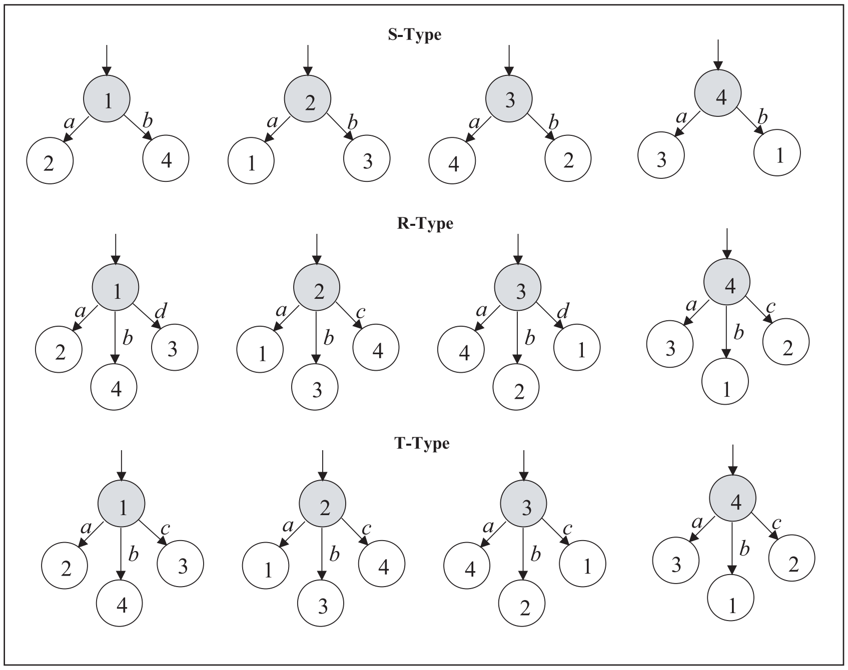
The communication payload designer evaluates the redundant network performance as a function of the number of simultaneous failures that can be recovered; the number of simultaneous failures that can be recovered without re-routing (i.e., using the redundancy equipment only); and the number of crossed switches.

The optimum design would minimize the number of crossed switches and the number of simultaneous failures that can be recovered without re-routing. Minimizing the number of crossed switches minimizes radiated power loss due to ohmic attenuation; minimizing the cases of re-routing assures service continuity in the channels not affected by the failure. Redundant network analysis can be a complex task that can be carried out using a computer-implemented algorithm.

Microwave switches

Microwave switches are the key elements of the redundant network design. Microwave switches are classified as R- (4-port, 4-position switch), S- (4-port, 2-positions switch) and T- (4-port, 3-position switch) type, as shown in Figure 6. The R- and S-type switches can be implemented either in coaxial or waveguide, whereas T-type switches can be implemented only in coaxial.

The switching function for the various switch types can be represented using the topological representation



▲ **Figure 7. Microwave switches modelization.**

ware simulates equipment failures and generates switch configurations for recovery.

To illustrate this theory, consider the input switching matrix of the 2/3 redundant network shown in Figure 8. The signal applied to input I1 enters port S1.1 (i.e., port 1 of the switch S1). The signal is directed to port S1.2 or port S1.4, depending on the state of the switch. In the first case, the signal is routed to output G1 from which it will be amplified by the nominal equipment. In the second case, the signal is routed through the S2 switch to output G2, where the redundant unit is connected. Therefore, the signal paths associated with input I1 can be schematically represented as shown in Figure 9(a). Likewise, the signal paths associated with input I2 are shown in Figure 9(b).

Each redundant network input corresponds to a path diagram in the form of a tree. The root of the tree corresponds to the input, the internal nodes represent the ports of the crossed switches and the leafs represent the possible outputs. The paths diagram representation is easily generalized to a redundant network composed of R- and/or T-type switches. The suggested modelization is well suited for high-level computer-language implementation, where ad-vanced data structures, such as concatenated lists, are available. A brief overview of the analysis algorithms follows.

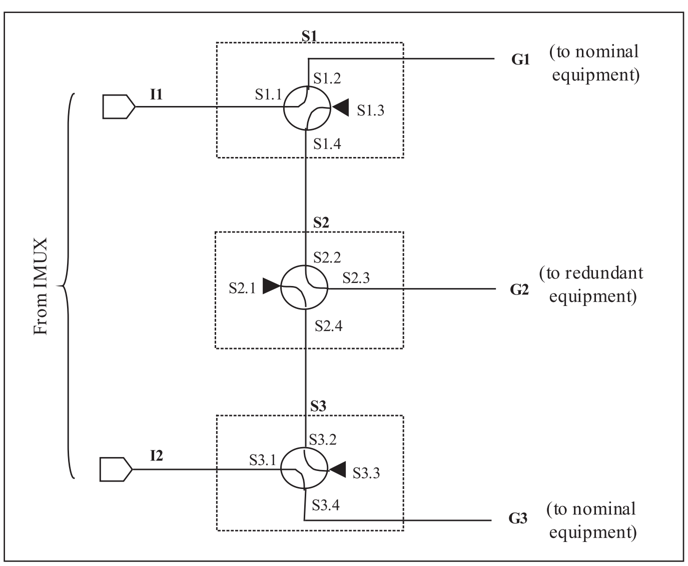
shown in Figure 7. Consider, for example the R-type switch. If the signal enters in the port 1, it is routed to port 2 if the switch is in position *a*, port 4 if the switch is in position *b* and port 3 if the switch is in position *d*. Likewise, if the signal enters port 2, it is routed to port 1 if the switch is in position *a*, port 3 if the switch is in position *b*, and port 4 if the switch is in position *c*.

Switching matrix analysis

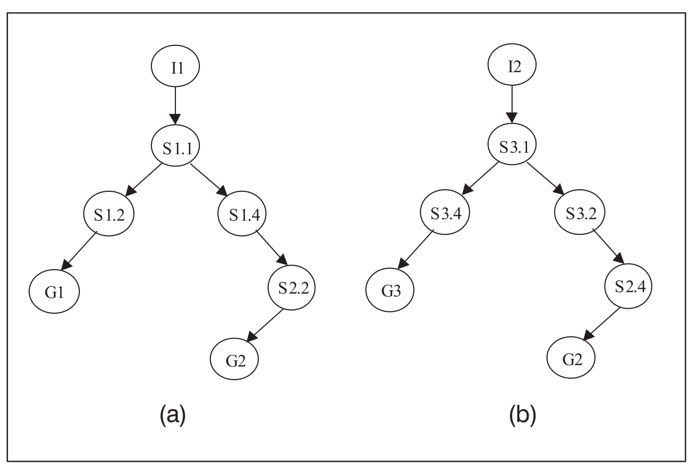
Redundant network analysis is based on the previous topological representation of the switching matrices. The proposed representation allows the implementation of efficient computer-oriented algorithms. Analysis soft-

Redundant network definition

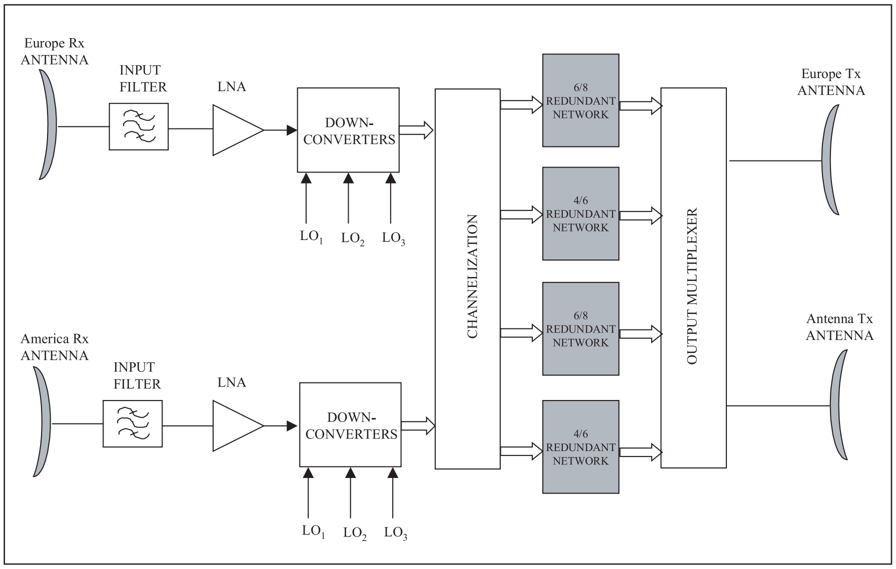
The redundant architecture is described for software analysis using a *netlist*. This approach allows for flexibility during the design phase. In addition, the design constraints related to amplifying equipment with different characteristics are easily implemented using this input format.



▲ **Figure 8. Schematic of a 2/3 input switching matrix.**



▲ **Figure 9. Topological representation of the 2/3 switching matrix: (a) input I1; (b) input I2.**



▲ **Figure 10. SATELCOM payload simplified block diagram.**

Tree generation

The tree associated with each redundant network input is generated by exploring the switching matrix architecture, as detailed in the previous example. Each node is associated with a linked list of the subtrees of that node. A linked list is used because there is no a priori restriction on its length. This allows each node to have an arbitrary degree within the tree hierarchy.

The tree generation is implemented using recursion, i.e., itself recursively visiting the subtrees of the given node until an empty tree is found.

Path finding

Once the trees for each network input have been generated, the relevant input/output paths are found by means of a back-pointing algorithm. A back-pointing algorithm visits the tree data structure from the leaves to the root (*tree traversal*), recovering all the signal paths related to the considered network input.

Switching Matrix	1 Failure		2 Failures	
	With Reconfig.	*Without Reconfig.*	*With Reconfig.*	*Without Reconfig.*
6/8	0	8	12	16

▲ **Table 1. Recovery capability of the 6/8 switching matrix.**

Switching Matrix	1 Failure	2 Failures
	Maximum Number of Crossed Switches	*Maximum Number of Crossed Switches*
6/8	1 (2 cases) 2 (6 cases)	1 (1 case) 2 (25 cases) 3 (2 cases)

▲ **Table 2. Crossed switches versus failures in the 6/8 switching matrix.**

Search for recovery configuration

The signal paths are then used to determine redundant network recovery configurations. This is accomplished by testing the compatibility between the signal paths relevant to each input while considering that two or more signal paths cannot share the same network ports and that signal crossing paths are only allowed for T-type switches. The output of this routine represents all the possible configuration of the redundant network under study.

Optimization

Optimization is performed on the basis of these user-defined criteria:

- Minimization of the number of crossed switches;
- Minimization of the cases of simultaneous failures that can be recovered only with re-routing;
- Minimization of some critical paths related to the payload physical architecture.

The analysis can be performed on the input or output switching matrix, because they have the same layout.

Implementation issues

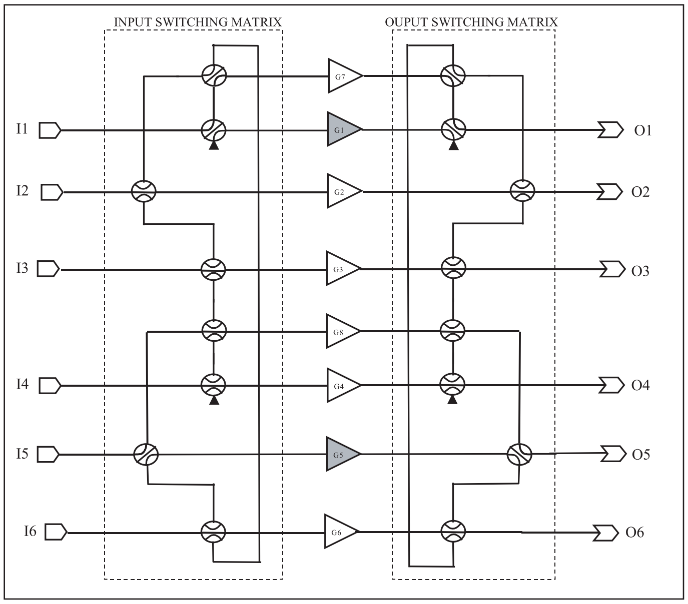
Technological and cost constraints have to be taken into account when designing redundant networks. First, although the input and the output switching matrices have the same layout, they are often implemented using different technologies, i.e., coaxial and waveguide, respectively. In fact, unlike the input switching matrix, losses in the output switching matrix are critical, since they lead directly to a reduction of the radiated power. Redundant network losses are minimized by implementing the output switching matrix in the waveguide.

Moreover, in large redundant networks, equipment is usually partitioned in a subset characterized by different values of the output power and bandwidth. This leads to a less flexible redundant network but drastically reduces the implementation costs.

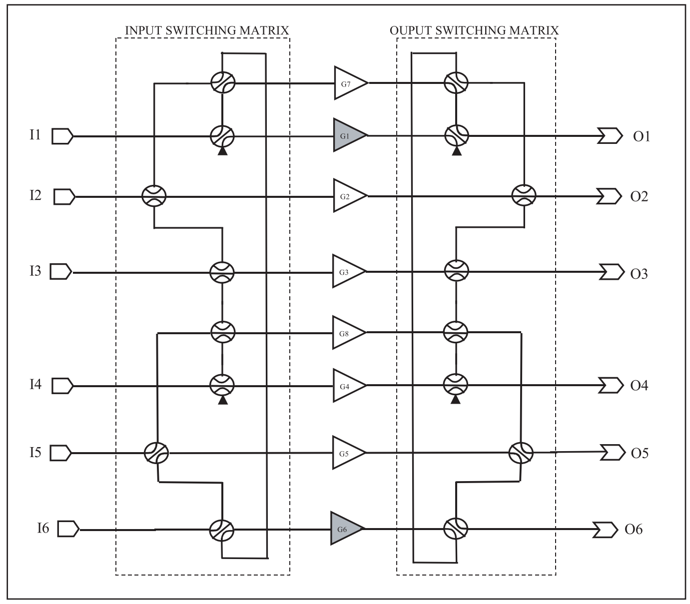
The analysis technique discussed in the previous section allows consideration of these design constraints.

Case study

The method outlined above has been successfully used for analyzing and designing redundant networks on SATELCOM payloads, which support a service area in Europe and North America and offer cross-connectivity capability. SATELCOM payloads operate in Ku-Band (i.e., 14/12 GHz), with channel bandwidths of 36 MHz, 54 MHz and 72 MHz.



▲ **Figure 11. Recovery of G1 and G5 failures in the 6/8 redundant network.**



▲ **Figure 12. Recovery of G1 and G6 failures in the 6/8 redundant network.**

The SATELCOM payload simplified top-level architecture is depicted in Figure 10. The transmitter section is based on four redundant networks for a total of 20 operational channels.

As a working example, we analyze in-depth the 6/8 redundant network of Figure 4. The redundant network recovery capability is indicated in Table 1. The maximum number of crossed switches for a given number of simultaneous failures is listed in Table 2.

For example, for G1 and G5 simultaneous failures, the simulation software indicates the recovery configuration shown in Figure 11. The proposed solution is optimum because it minimizes the number of crossed switches, thus reducing power loss.

If G1 and G6 fail simultaneously, the simulation software finds the recovery configuration indicated in Figure 12. In this case, the re-routing process takes place: the channel entering into the I5 input must be redirected to the G8 amplifying chain, although its nominal equipment (i.e., G5) has not failed. This is necessary in order to recover G8.

In general, the re-routing occurrences should be limited as far as possible because they determine a temporary traffic loss in a communication channel not affected by equipment failure.

Reliability analysis

The reliability $R(t)$ of a system is defined by the probability of the correct operation of the system at the time t:

$$R(t) = 1 - F(t) \tag{1}$$

The failure distribution $F(t)$ is the probability of an item failing in the time interval $0 \le \tau \le t$:

$$F(t) = \Pr\{\tau \le t\} = \int_0^t f(\tau) d\tau \tag{2}$$

where $f(t)$ is the probability density function of the time to failure t.

The instantaneous failure rate $\lambda(t)$ of a given equipment is defined as:

$$\lambda(t) = \lim_{\Delta t \to 0} \left[\frac{N(t) - N(t + \Delta t)}{N(t)} \right] \tag{3}$$

where $N(t)$ is the number of pieces in a correct operating state at the time t. Instantaneous failure rate is usually expressed as number of failures in 10^9 hours (FIT).

A typical failure rate versus time curve is given in Figure 13 (bathtub curve). In general, the life stages of the product consist of early, chance and wear-out periods. For space equipment, the early failures are eliminated before launch by means of a special thermal test (burn-in). In addition, the useful lifetime of the components exceeds the satellite mission. Therefore, "infant mortality" and wear-out failures are excluded in the following analysis. Under the above assumptions, the failure rate can be assumed constant and the reliability can be shown to be

$$R(t) = \exp(-\lambda t) \tag{4}$$

Redundant network reliability is a function of the input-output switching matrices and the microwave amplifier reliabilities. The microwave switch pairs status can be described in terms of the events set $\{G, B\}$, where G indicates that the switches are functioning upon telecommand ("good") and B indicates that the switches have failed ("bad"). The switch failure event B includes the cases in which the switches are stuck in one of the stated positions. However, it should be noted that when a switch pair becomes stuck in one position, it provides connectivity through the ports between which it is blocked. Therefore, the above switch failure definition leads to conservative estimates of transmitter reliability.

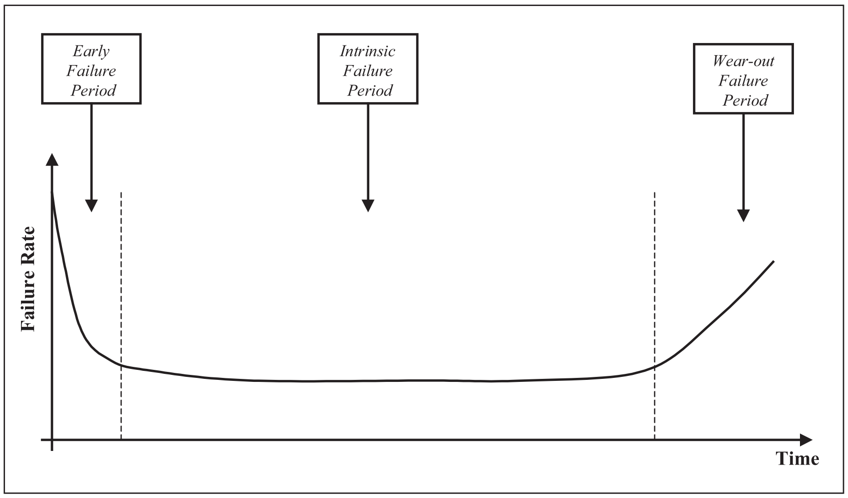
Let p_s and q_s represent the probabilities of success (event G) or failure (event B) for a switch pair (i.e., a pair formed by a switch in the input matrix and its correspondent in the output matrix). Simultaneously, let p_a and q_a represent the probabilities of success or failure for a microwave amplifier (SSPA or TWTA).

Considering a M/N (with $N > M$) redundant network, the probability ($P_{M/N}$) that all M communication channels are operational can be written as follows:

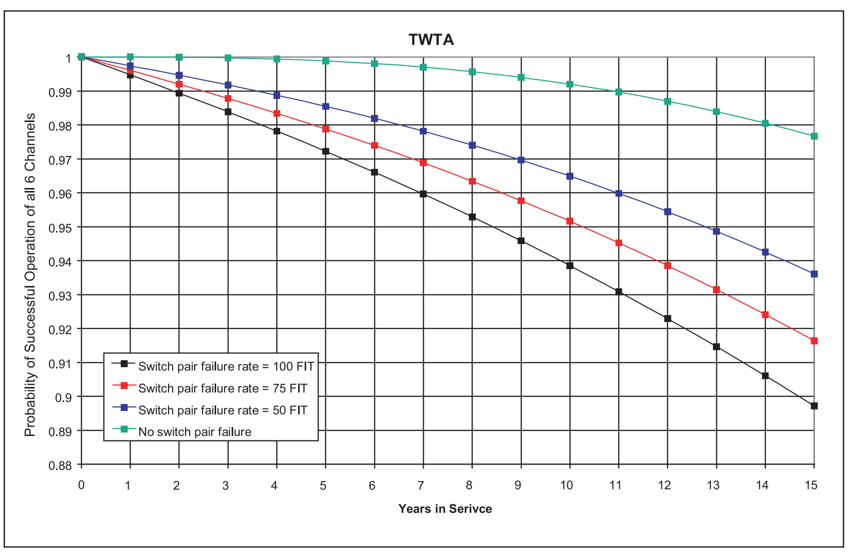
$$P_{M/N} = \sum_{i=M}^{N} \left\{ \left[p_A^i \cdot q_A^{(N-i)} \right] \cdot \sum_{j=n_{s,\max}(i)}^{n_{s,\max}(i)} k_j p_s^{n_s(j)} \right\} \quad (5)$$

where the following constraint holds:

$$\sum_{j=n_{s,\min}(i)}^{n_{s,\max}(i)} k_j = \binom{N}{i} \quad (6)$$



▲ **Figure 13. The "bathtub" failure model.**



▲ **Figure 14. Reliability analysis diagram for the TWTA case in the 6/8 redundant network.**

In the above relationships, the coefficient k_j represents the number of cases in which the considered failures (varying from 0 to $N - M$) require $n_s(j)$ functional switch pairs to recover them. For a given number i of operational channels, the required number of functional switches will vary from $n_{s,\min}(i)$ to $n_{s,\max}(i)$. If $p_s = 1$, the probability that all communication channels are operating is given by the binomial expansion

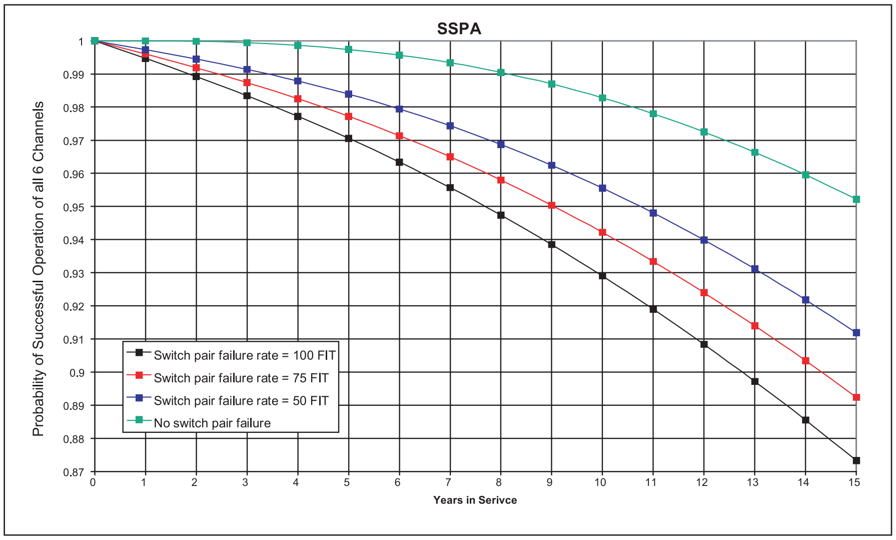
$$P_{M/N} = \sum_{i=M}^{N} \binom{N}{i} p_A^i \cdot q_A^{(N-i)} \quad (7)$$

Evaluating Equation (5) could be a rather lengthy process due to the calculus of the coefficient k_j and the exponent $n_s(j)$. The above coefficients are determined once the switching matrix analysis is finished.

For example, consider the redundant network with $M = 6$, $N = 8$. In this case, Equation (5) and the simulation results yield:

$$P_{6/8} = p_A^8 \cdot p_S^6 + p_A^7 \cdot q_A \cdot \left(2p_S^6 + 6p_S^7\right) + p_A^6 \cdot q_A^2 \left(p_S^6 + 10p_S^7 + 17p_S^8\right) \quad (8)$$

The probability of successful operation of all six communication channels as a function of the years in service has been evalu-



▲ **Figure 15. Reliability analysis diagram for the SSPA case of the 6/8 redundant network.**

ated for a travelling wave tube amplifier (TWTA) with failure rate of 660 FIT and a solid state power amplifier (SSPA) with failure rate of 880 FIT. The failure rates have been chosen according to the extensive "in-orbit" reliability study reported in [2].

The analysis results for the TWTA case are plotted in Figure 14, and the results for the SSPA case are plotted in Figure 15, taking into account various switch pair failure rates.

Conclusion

This article has discussed a topological approach for redundant network analysis and design techniques. The proposed tool is indicated for highly complex redundant networks, such as those planned for future satellite payloads. The simulation software outlined throughout the paper has successfully employed for the design of SATELCOM, AMOS and EXPRESS AM payloads at Alenia Spazio.

Theoretical analysis, practical implementation issues and case analysis provided in the paper offer a wide coverage of the topic. ■

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