WHITE PAPER

Modeling and minimizing failure rate in a modular system

Jacques Macherel, *senior product line manager, Oscilloquartz SA, Switzerland*

An operator must be able to evaluate the availability of any service they provide and when that service will be at risk. That analysis depends on the equipment they use, and becomes complicated when using modular systems. In that case, each module contributes to the reliability and availability of any service. The operator will use this analysis to determine the best equipment configuration, which items must be provisioned as spare parts, and the degree of maintenance required for providing reliable services.

The purpose of this paper is to give a better understanding of the different terms used in reliability calculations, to present a simple and efficient calculation model to evaluate the number of failures in a modular system, and to demonstrate the benefits of redundant configurations on service availability.

I. Introduction

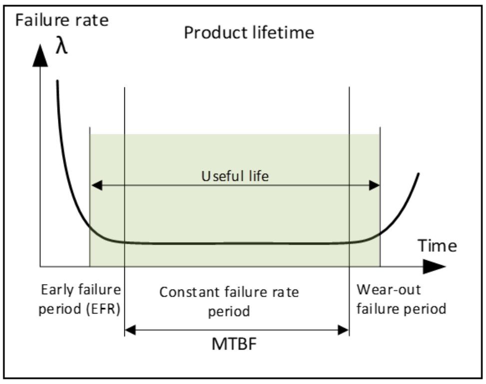
Any company providing services must be able to guarantee the specified level of accuracy and availability. This is particularly true in critical infrastructure such as telecommunications, energy distribution companies, broadcasting or finance. One big challenge is the reliability of services and how to manage their vulnerabilities. It is important to be able to evaluate the risk of failure, to anticipate the need for spare parts and to identify weaknesses of equipment or critical areas of a network.

II. Definitions

Mean time between failures (MTBF)

MTBF is a characteristic defining the average period (in hours) between two successive failures of a module. This value is based on reliability algorithms and standards like MIL HDBK-217 or Telcordia SR-332. The latest issue, Telcordia SR-332 issue 4, is the one we will use here. It describes different methods (methods I to III) for calculating MTBF values. Method III is used when the real number of failures from the field is available. For new products that do not have sufficient history to build such statistics, methods I or II are used. All methods use failure in time (FIT) numbers related to the components of the module. The FIT value for every component is either calculated based on the standard or is documented by the component's manufacturer and is applicable for specified environmental conditions.

MTBF is calculated during the life of the product during which the average number of failures has reached a constant value. The product's early failure period (EFR) and the product's wear-out period are excluded from the calculations because the failure rate during these periods usually evolves in a non-linear way, as shown below.



During the period of constant failure rate, it is assumed that the number of failures is constant. However, the moment at which these failures occur is 100% random.

MTBF versus lifetime

MTBF is often wrongly associated with the lifetime of a product. In reality, these two characteristics have no relationship. The lifetime of a product defines the number of years for which the product has been developed. The lifetime is influenced by the choice of technology, choice of components, their operating conditions and how the product is designed. Thus, a product may have been developed for a lifetime of 10 or 15 years, while having an MTBF of several hundreds or even thousands of years, depending on the components and how they are used. As such, the fact that a product or a module has an MTBF of 1 million hours does not suggest the unit will operate for 114 years. Instead, a better representation would be if 500 units operated at the same time, a failure could be expected every 2,000 hours, or 83 days.

Failure rate λ (lambda)

The failure rate is expressed by the Greek letter λ (lambda) and is used for reliability calculation. The failure rate λ is the reciprocal of MTBF:

$$\lambda = \frac{1}{\mathrm{MTBF}}$$

Mean time to repair (MTTR) / mean time to failure (MTTF)

MTTR is the time (in hours) required to repair a component or a module. MTTR includes the time from when the service provided by this component fails until the moment when the service is again available. MTTR is applicable for equipment and modules that can be repaired. In case the module or equipment cannot be repaired, we would use the term MTTF.

Availability

A service or function provided by equipment is expected to be available at any time and without interruption as long as the equipment is in operation. Unfortunately, this is not the case and, as we have seen previously, equipment is subject to random failures.

The ***availability*** is an indicator expressing when the service is usable as a percentage of the total operating time. The period during which the service is available is called "***uptime***," and the period during which the service is unavailable is called "***downtime***."

Availability is characterized as:

$$\mathrm{availability} = \frac{\mathrm{uptime}}{\mathrm{uptime} + \mathrm{downtime}}$$

Substituting MTBF as previously defined, we have:

$$\mathrm{availability} = \frac{\mathrm{MTBF}}{\mathrm{MTBF} + \mathrm{MTTR}}$$

The *availability* of the service is generally expressed as the number of "9" contained in its value. This makes it very easy to express the downtime that can be expected in a desired period of time. This information is useful for establishing maintenance contracts, the need for spare parts, and programming maintenance periods.

Example of typical downtime over a period of one year (8,760 hours) for different degrees of availability:

$$\mathrm{downtime} = \frac{8{,}760}{\mathrm{availability}} - 8{,}760$$

Availability	Number of nines	Downtime per year
99.9%	Three nines	8.76 h
99.99%	Four nines	52.5 min
99.999%	Five nines	5.26 min
99.9999%	Six nines	31.5 sec
99.99999%	Seven nines	3.15 sec
99.999999%	Eight nines	0.32 sec

III. Calculations

Service MTBF for a non-redundant system

In the MTBF calculation of a system, we normally only consider the modules essential to perform the service provided by the system. For example, failure of a management module would not affect the service of the system, so it is not included. In contrast, if the module is necessary for the service to run, then this module must be included in the calculation.

In the case of a modular system, MTBF values for each of the modules are represented in a block diagram as modules in a series.

Any module failure affects the entire system:

$$\mathrm{MTBFservice} = \frac{1}{\lambda\mathrm{module1} + \lambda\mathrm{module2} + \lambda\mathrm{module3}}$$

Example 1 – non-redundant system

Module1 → MTBF= 1,000,000 h (114 years) → λmodule1 = $1E^{-6}$

Module2 → MTBF = 600,000 h (68.5 years) → λmodule2 = $1.67E^{-6}$

Module3 → MTBF = 400,000 h (45.7 years) → λmodule3 = $2.5E^{-6}$

$$\text{MTBF service} = \frac{1}{1E^{-6} + 1.67E^{-6} + 2.5E^{-6}}$$

= 193,548 h = **22 years**

In this example, we should expect to see one system failure every **22 years**. This calculation highlights the fact that the MTBF for the overall system will always be smaller than the value of the module with the smallest MTBF in the chain.

Impact on number of failures

Someone might think that one failure every 22 years is acceptable for equipment with life expectancy of 10 to 15 years. Yet this situation becomes critical when we consider a network of **100** units like this one. In this case, we would expect one system failure every:

$$t = \frac{193{,}548}{100 * 24} = \mathbf{80.6\ \textit{days}}$$

Impact on the availability

Adding the MTTR into the calculation allows us to calculate the availability, which in this example will give a very poor system availability. Here is an example with an MTTR of 3 days (72 hours):

$$\text{availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} = \frac{193{,}548}{193{,}548 + 72}$$

= **99.9628%** (three nines)

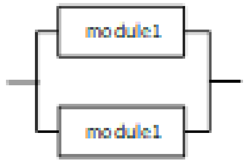
Over a one-year period, this availability would represent a downtime of **3.25 hours**, which for many services would not be acceptable.

To improve the situation, there are two main options:

1. Use components with higher MTBF values
2. Opt for redundancy

Service MTBF for a redundant system

A system with redundant modules has one or more standby modules that can take over if an active one fails. The block diagram for the group of modules is represented as operating in parallel.



To calculate the failure rate of this block ($\lambda_{redundant}$), we need to include the MTTR, because we cannot exclude the possibility that a second failure occurs during the period in which the first module is still unavailable. This time is indicated with the Greek letter μ (mu), which is the reciprocal of MTTR:

$$\mu = \frac{1}{\text{MTTR}}$$

A probability formula is now used to calculate the failure rate in the redundant block while taking into consideration the MTTR:

$$\lambda_{redundant} = \frac{2 * (\lambda\text{module})^2}{\mu}$$

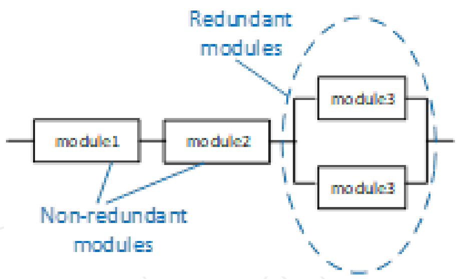
The MTBF value for the block is calculated as follows:

$$\text{MTBF}_{redundant} = \frac{1}{\lambda\text{redundant}}$$

Importance of redundancy in the entire system

Partially redundant configuration

We now consider the same configuration as in Example 1 but with the addition of the redundancy on the module with the lowest MTBF value. We can represent the block diagram as follows:



Example 2 – partial redundancy

Considering MTTR = 3 days (72h):

Module1 → MTBF= 1,000,000 h (114 years) → $\lambda_{module1}$ = $1E^{-6}$

Module2 → MTBF = 600,000 h (68.5 years) → $\lambda_{module2}$ = $1.67E^{-6}$

Module3 → MTBF = 400,000 h (45.7 years) → $\lambda_{module3}$ = $2.5E^{-6}$

Group3 → MTBF = $1.11E^{9}$ h (126,832 years) → λ_{group3} = $9.0E^{-10}$

MTBF for the entire system is calculated as:

$$\text{MTBFservice} = \frac{1}{\lambda\text{module1} + \lambda\text{module2} + \lambda\text{group3}}$$

$$= 374{,}873\ h = \mathbf{42.8\ years}$$

In the case where 100 devices are deployed in the network, this would represent one failure every:

$$\text{MTBF} = \frac{1}{\lambda\text{total} * 100} = 3{,}749\ hours = \mathbf{156\ days}$$

Availability:

$$\text{availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} = \frac{374{,}873}{374{,}873\ + 72}$$

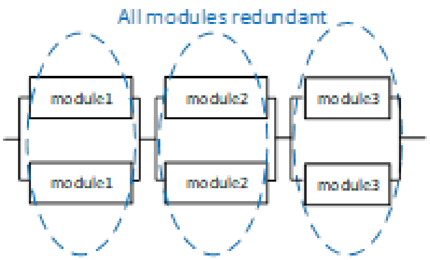
= **99.981%** (three nines)

Over a one-year period, this availability still represents a downtime of **1.68 hours**, which is only a very small improvement compared with the previous example.

The module(s) with the lowest MTBF will most significantly impact the MTBF and availability of the total system. So having a single module operated in redundant mode brings only very limited improvement.

Fully redundant configuration

Let's take a configuration where all modules from the chain are configured in redundant mode, block diagram will appear as follows:



Example 3 – full redundancy

Considering MTTR = 3 days (72h):

Group1 → MTBF= 6.94 E^9 h (792,744 years) → λ_{group1} = 1.44E^{-10}

Group2 → MTBF = 2.5 E^9 h (285,388 years) → $\lambda_{module2}$ = 4.0E^{-10}

Group3 → MTBF = 1.11E^9 h (126,839 years) → λ_{group3} = 9.0E^{-10}

$$\text{MTBFservice} = \frac{1}{\lambda\text{group1} + \lambda\text{group2} + \lambda\text{group3}} = 6.93\text{E}^8\ h$$

$$= \mathbf{79{,}054\ years}$$

$\text{availability} = \frac{\text{MTBF}}{\text{MTBF+MTTR}}$ = 99.99999896% (seven nines)

Over a one-year period, this availability represents a downtime of only **3.29 seconds**, which is incomparably better than all other configurations.

IV. Conclusions

Redundancy, MTTR and spare parts are the drivers for implementing a system with high levels of availability. Here are the details.

Redundancy

We have now analyzed these 3 examples of modular systems. We showed that a configuration where all modules operated in a redundant mode is dramatically better than any other configuration. However modular systems can rarely be configured for full redundancy. In this case, it is important to understand which modules are non-redundant, and to evaluate the impact on the overall MTBF and availability.

If the target is to reach an availability in the order of six nines or better (99.9999%), this level of availability is likely to require a fully redundant system.

MTTR

We see that MTTR is a key parameter influencing the number of failures and the availability of service.

In the case of full redundant configuration like illustrate in the Example 3, we can calculate the impact of MTTR on the availability (and downtime) as follows:

MTTR (days)	Availability	number of nines	Downtime (over 1 year)
93	99.990010%	four nines	52.5 min
29	99.999028%	five nines	5.10 min
9	99.999906%	six nines	29.5 sec
3	99.999990%	seven nines	3.28 sec
1	99.999999%	eight nines	0.36 sec

Spare parts

To ensure service availability, operators must reduce the MTTR with spare parts distributed at strategic locations, enabling quick and efficient repairs. Doing so will ensure maximum service availability, minimum downtime and sufficient time to repair the faulty module.