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Reliability Analysis of Transmission Requirements in Communication Satellite Systems

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An analytical relationship is derived between the reliability of the on-board power section of communication satellite systems and the effective isotropic radiated power requirement. The latter plays a key role in system design, yielding a direct impact on transmitter configuration and technological features, as well as on the critical compromise between transmitter and antenna specifications. Through the proposed approach, the impact of antenna complexity on the payload reliability is also evaluated. The analysis has been oriented to a design methodology of satellite payloads able to account for reliability constraints in a very early stage of system assessment. The methodology has been applied to a feasible satellite system. The achieved results confirm the usefulness and the potential of the approach.

Nomenclature

$F_X^{(i)}(t)$ = distribution function of $X^{(i)}$
G_A = antenna gain
$G_d^{(i)}$ = power gain of the ith amplifier devices
$I_{dc0}^{(i)}$ = rf power-independent component of the ith amplifier dc current
$\mathrm{MTTF}_d^{(i)}$ = mean time to failure of the ith amplifier devices
$m_\alpha^{(i)}$ = Arrhenius curve parameter of the ith amplifier devices
N_A = number of active power amplifiers
$N_{a(j)}$ = number of active amplifiers in the jth block
N_b = number of blocks in the power section
$N_d^{(i)}$ = number of power devices of the ith amplifier
N_r = number of antenna radiators
$N_{r(j)}$ = stand-by amplifiers in the jth block
n_j = set of index values of the active amplifiers in the jth block
$P_{Dd}^{(i)}$ = dissipated power of each device of the ith amplifier
$P_{rfa}^{(i)}$ = rf power required from the ith amplifier
$P_{rfd}^{(i)}$ = rf power required from each device of the ith amplifier
$q_\alpha^{(i)}$ = Arrhenius curve parameter of the ith amplifier devices
$R(t)$ = reliability of the power section
$R_A^{(j)}(t)$ = reliability of the jth block
$R_{ch\text{-}c}^{(i)}$ = channel-to-case thermal resistance of the ith amplifier devices
r = number of redundant (stand-by) amplifiers
T = operational time
$T_c^{(i)}$ = case temperature of the ith amplifier devices
$T_{ch}^{(i)}$ = channel temperature of the ith amplifier devices
$V_{dc}^{(i)}$ = dc voltage of the ith amplifier
$X^{(i)}$ = time to failure (or life length) of the ith amplifier

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$\beta_A^{(i)}$ = failure rate of the ith amplifier in the device useful life
$\beta_A^{(i,j)}$ = failure rate (useful life) of ith active amplifier in the jth block
$\beta_A^{(i)}(t)$ = failure rate of the ith amplifier
$\beta_d^{(i)}$ = failure rate of the ith amplifier devices in the useful life
$\beta_d^{(i)}(t)$ = failure rate of the ith amplifier devices
$\beta_i^{(j)}$ = failure rate of the input redundancy switch box of the jth block
$\beta_o^{(j)}$ = failure rate of the output redundancy switch box of the jth block
$\beta_S^{(k,j)}$ = failure rate (useful life) of kth redundant amplifier in the jth block
$\eta_{bo}^{(i)}$ = back-off efficiency of the ith amplifier
$\eta_c^{(i)}$ = combining efficiency of the ith amplifier devices
$\eta_d^{(i)}$ = efficiency of the ith amplifier devices
η_0 = power section-to-antenna connection efficiency
$\Lambda^{(j)}(t)$ = Poisson random variable parameter for the jth block
$\mu^{(i)}$ = mean value of $\ell n X^{(i)}$
ξ = modulation factor
$\sigma^{(i)}$ = standard deviation of $\ell n X^{(i)}$

Introduction

IN satellite systems for both fixed and mobile applications the on-board transmitting section represents a crucial part of the payload in the assessment of both technological feasibility and reliability of the overall payload. In recent years, extensive efforts have been devoted to analyze the technological feasibility of payloads and, in particular, of solid-state and tube-based power sections.[1] Furthermore, system requirements have been classified, accounting for their impact on the on-board transmitter characteristics, to identify at the system level the criticalities that may arise in the design of the payload power section.[2]

As far as transmitter reliability is concerned, solid-state lifetime verification and space qualification problems, basically solved for tubes, are still in progress for solid-state amplifiers.[1,3,4] A second point concerns the role of on-board transmitter reliability in the design of satellite systems. Reliability estimation often represents only a checkpoint in the overall system performance evaluation.[1] The consequent need for a time-consuming tuning of the designed system configuration can be overcome by establishing a direct relationship between on-board transmitter reliability and transmitter-related system requirements that can be advantageously utilized in the payload design.

In this frame, the relationship between the reliability of the on-board solid-state transmitter and an important system requirement, the effective isotropic radiated power (EIRP), is derived, as the latter has a direct impact on transmitter configuration and technological features. In addition, the EIRP is directly related to the antenna characteristics and complexity. To this respect, the proposed approach is also useful to relate the effects of the transmitter-vs-antenna compromise to the transmitter reliability. The approach is presented together with some of the achieved results, pointing out the potential and the effectiveness of the proposed methodology in the frame of a reliability-oriented design context.

Power Section Architecture

The transmitting side of the payload has been configured as depicted in Fig. 1. Most of the beam forming network (BFN-A) is assumed to precede power amplifiers, the latter being eventually followed by a final low-loss stage of the BFN (BFN-B). The power section could be composed of differently sized power amplifiers or dual amplifier pairs or multiport amplifier, the latter two approaches allowing an even distribution of the overall power demand among the $N_A \geq 1$ amplifiers.[5,6] The antenna is supposed to consist of N_r radiators (N_r may be different from N_A), either in direct radiating array configuration or organized in a feed cluster located in the focal plane of a main reflector.

In the general case, the rf power (watt) required from the ith of the N_A amplifiers (in Fig. 1, as an example, the output power

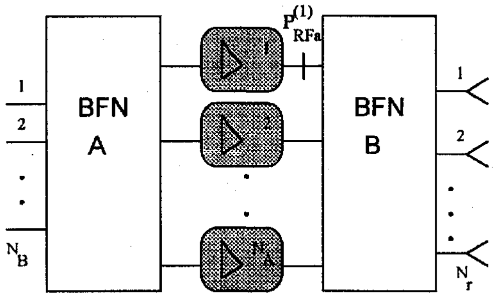

Fig. 1 Block diagram of the modeled payload transmitting side.

of amplifier 1 is shown) is related to the EIRP requirement (watt) through the following expression:

$$P_{rfa}^{(i)} = \frac{\mathrm{EIRP}}{G_A \eta_0} - \sum_{\substack{j=1 \\ j \neq i}}^{N_A} P_{rfa}^{(i)} \tag{1}$$

for $i = 1, \ldots, N_A$, where η_0 accounts for losses resulting from the BFN-B, redundancy circuits, and connections (cables, etc.). A common efficiency value has been adopted for all of the BFN-B outputs, reasonably assuming that in the payload losses resulting from different path lengths are properly compensated. If the use of a direct radiating array is assumed, the antenna gain can be exploded in terms of the gain factor of each array element and N_r: in this case, expression (1) provides, for a given EIRP requirement, a direct insight in the effects of trading off power demand and antenna complexity.

Reliability Modeling of Power Devices

The rf linear power requirement from the ith amplifier ($i = 1, \ldots, N_A$), which has been expressed in terms of EIRP requirement, must be related to the dissipated power of the ith amplifier, to involve the reliability parameters of the power devices. In particular, assuming the use of solid-state technology in the power amplifiers and, in particular, of metal-semiconductor field-effect transistors as power devices, the dissipated power is used to evaluate the device channel temperature. A certain back-off level is generally applied to the amplifiers to meet the linearity requirements: this can be accounted for through $\eta_{bo}^{(i)} \leq 1$, where $\eta_{bo}^{(i)} = 1$ means that back off is not applied. The rf power requirement from the ith amplifier is then typically met by paralleling a number of devices. Assuming, very reasonably, that the same power is required from all devices of the ith amplifier, the linear rf output power in watts required from each device of the ith amplifier ($i = 1, \ldots, N_A$) is given by

$$P_{rfd}^{(i)} = \frac{P_{rfa}^{(i)}}{\eta_c^{(i)} N_d^{(i)}} \tag{2}$$

The relationship between rf output power and dissipated power of each device of the ith amplifier is mainly dictated by the polarization class selected for the power devices. In satellite applications, a very interesting compromise between amplifier efficiency and linearity is reached through the use of harmonic controlled amplifiers.[5,6] Under the latter assumption, the dissipated power of each device of the ith amplifier ($i = 1, \ldots, N_A$) can be expressed as

$$P_{Dd}^{(i)} = \left[I_{dc0}^{(i)} V_{dc}^{(i)} + \left(\frac{\xi P_{rfd}^{(i)}}{\eta_d^{(i)}} \right) \right] - \left(1 - \frac{1}{G_d^{(i)}} \right) P_{rfd}^{(i)} \tag{3}$$

where the term within the brackets represents the device dc power consumption in watts. The channel temperature (degrees, celsius) of the ith amplifier devices ($i = 1, \ldots, N_A$) can be obtained through the expression[3]

$$T_{ch}^{(i)} = T_c^{(i)} + R_{ch\text{-}c}^{(i)} P_{Dd}^{(i)} \tag{4}$$

The value of the channel-to-case thermal resistance is available in the data sheet of the selected power devices. The case temperature can be related to the on-board temperature requirements and the thermal design parameters of the whole amplifier. The device channel temperature of the ith amplifier can be related to the mean time to failure of the device through the Arrhenius plots. The latter, which are provided by the device manufacturer, display the following experimental relationship between the mean time to failure (hours) and the channel temperature in degrees Kelvin of the ith amplifier device, for the given failure mechanism:

$$\ln\{\mathrm{MTTF}_d^{(i)}\} = m_\alpha^{(i)}/T_{\mathrm{ch}}^{(i)} + q_\alpha^{(i)} \tag{5}$$

where $i = 1, \ldots, N_A$. The curve parameters $m_\alpha^{(i)}$ and $q_\alpha^{(i)}$ depend on the failure mechanism (e.g., gate electromigration, ohmic contact degradation[7,8]) through a parameter α. In particular, $m_\alpha^{(i)}$ is proportional to the device activation energy.

At this point, a further step is required to complete the reliability-to-EIRP modeling. In fact, $\mathrm{MTTF}_d^{(i)}$ must be related to the failure rate in FIT (failures per interval of time of 10^9 h) of each device of the ith amplifier in the desired operational time interval and, then, to the amplifier failure rate. The devices of the power amplifiers are assumed to follow the widespread bathtub life model, which, as is well known, consists of three phases, each of them characterized by a different behavior of the failure rate[9]: the failure rate decreases with time in the early life or infant mortality phase, it keeps fairly constant in the useful life, and, finally, it increases with time in the wear-out phase. In what follows the operational time of interest is supposed large enough so that power amplifiers can be considered in the useful life and, hence, can be characterized by a time-constant failure rate. The relationship between $\mathrm{MTTF}_d^{(i)}$ and the failure rate of the ith amplifier devices can be obtained by taking into account that the time-to-failure experimental data of semiconductor devices in the useful life can be very well fitted assuming a lognormal distribution for the time to failure.[10] Through the lognormal model, the device failure rate can be obtained, and its value $\beta_d^{(i)}(T)$, which corresponds to the operational time of interest T, can be reasonably considered to represent the fairly constant device failure rate $\beta_d^{(i)}$ in the useful life portion of the bathtub model. The device failure rate can be expressed as the ratio between $\mathrm{d}F_X^{(i)}(t)/\mathrm{d}t$ and the reliability $R_X^{(i)}(t) = 1 - F_X^{(i)}(t)$. Considering the normal variable $\ln X^{(i)} \sim N(\mu^{(i)}, \sigma^{(i)})$ and setting $\theta^{(i)}(t) = t/\mathrm{MTTF}_d^{(i)}$, after manipulations, the failure rate of the ith amplifier devices ($i = 1, \ldots, N_A$) can be expressed as

$$\beta_d^{(i)}[\theta^{(i)}(t)] = \sqrt{\frac{2}{\pi}}\,\frac{\exp\{-[\Xi^2(\vartheta^{(i)}(t), \sigma^{(i)})]\}}{\vartheta^{(i)}(t)\sigma^{(i)}\mathrm{MTTF}_d^{(i)}\mathrm{erfc}\{\Xi(\vartheta^{(i)}(t), \sigma^{(i)})\}} \tag{6}$$

with

$$\Xi\{\theta^{(i)}(t), \sigma^{(i)}\} = \frac{\ln[\theta^{(i)}(t)\exp\{\sigma^{(i)2}/2\}]}{\sigma^{(i)}\sqrt{2}}$$

where erfc{ } is the error function complement.

By setting $t = T$ in Eq. (6), the failure rate $\beta_d^{(i)} = \beta_d^{(i)}[\theta^{(i)}(T)]$ of each of the ith amplifier devices can be obtained. The relationship in Eq. (6) is also available in the form of normalized curves, displaying the product (failure rate) $\times$ MTTF in FIT $\times$ hours as a function of $\theta(t) = t/\mathrm{MTTF}$, for a given standard deviation.[10] The lognormal formulation can be utilized by entering Eq. (6) or the normalized plots with the value of $\sigma^{(i)}$. The latter can be estimated through different approaches, all based on data provided by the device manufacturer.

The failure rate $\beta_A^{(i)} = \beta_A^{(i)}(T)$ ($i = 1, \ldots, N_A$) can be found from $\beta_d^{(i)}$, taking into account that the devices are in series from the reliability point of view and, therefore,

$$\beta_A^{(i)} = N_d^{(i)}\beta_d^{(i)} \tag{7}$$

Redundancy Structure and Reliability-to-EIRP Relationship

To complete the reliability modeling of the power section, the redundancy strategy and degree must be characterized.

In satellite applications the stand-by redundancy, where the active power modules are connected through switches to additional amplifiers in parallel, is a widespread approach to counteract component failures and, hence, to improve system reliability. Stand-by redundancy is hence assumed in modeling the on-board power section, where N_A amplifiers are active (main) and r are redundant (stand by). In particular, the active amplifiers are organized in $N_b \geq 1$ blocks. The jth block is composed of $N_{a(j)}$ active amplifiers, out of the N_A active ones, and $N_{r(j)}$ out of the r stand-by modules. The latter are included for redundancy through proper switches. A general schematic of the resulting $(N_A + r) : N_A$ structure is depicted in Fig. 2, without showing the organization in blocks for the sake of simplicity. The input and output redundancy switching modules, whose complexity is dictated by the values of N_A, r, N_b, $N_{a(j)}$, and $N_{r(j)}$ ($j = 1, \ldots, N_b$), are pointed out in Fig. 2.

The failure rate of the ith ($i = 1, \ldots, N_A$) amplifier is hereinafter indicated as $\beta_A^{(i,j)}$, where the index j has been added to the symbol adopted in Eq. (7) to point out that the ith amplifier belongs to the jth ($j = 1, \ldots, N_b$) block. The failure rates of the N_A active amplifiers are supposed to differ only as a consequence of the different rf power requirements. Therefore, the failure rate of the kth ($k = 1, \ldots, r$) stand-by amplifier, belonging to the jth ($j = 1, \ldots, N_b$) block, which becomes active to replace the ith ($i = 1, \ldots, N_A$) module within the same jth block, is $\beta_S^{(k,j)} = \beta_A^{(i,j)}$ ($i = 1, \ldots, N_A$; $j = 1, \ldots, N_b$; $k = 1, \ldots, r$), whereas $\beta_S^{(k,j)} = 0$ ($j = 1, \ldots, N_b$; $k = 1, \ldots, r$) when the kth stand-by module is not active. Obviously, for a given structure of the power section, only a sub-set of the possible (i, j) pairs are meaningful.

Under the preceding assumptions and taking into account that the $N_{a(j)}$ active modules (either the main ones or those replaced after failure) of the jth block are in series from the reliability point of view, as they must all work to assure the system correct behavior, the number of failures in the time interval $(0, t)$ can be modeled as a Poisson random variable whose parameter is

$$\Lambda^{(j)}(t) = \left\{\sum_{i \in n_j} \beta_A^{(i,j)}\right\} t \qquad (j = 1, \ldots, N_b) \tag{8}$$

Therefore, the reliability of the redunded power amplifiers in the jth block ($j = 1, \ldots, N_b$) can be evaluated as the probability that no more than $N_{r(j)}$ modules fail in the time interval $(0, t)$, hence by adding the Poisson probabilities that k modules ($k = 0, \ldots, N_{r(j)}$) fail in $(0, t)$ (Ref. 9). In deriving $R_A^{(j)}(t)$, it is also assumed that the input and output redundancy switch boxes of the jth block are characterized by constant failure rates and that they are connected in series with the jth block power amplifiers. Therefore, the reliability of the jth block ($j = 1, \ldots, N_b$) is given by

$$R_A^{(j)}(t) = \exp[-(\beta_i^{(j)} + \beta_o^{(j)})t]\left\{\exp[-\Lambda^{(j)}(t)]\sum_{k=0}^{N_r(j)} \frac{[\Lambda^{(j)}(t)]^k}{k!}\right\} \tag{9}$$

The reliability of the power section can be then evaluated taking into account that the power blocks are in series from the reliability

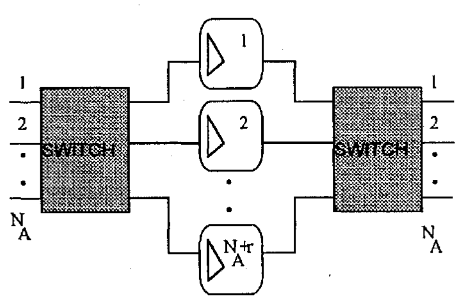

Fig. 2 Stand-by redundancy of the on-board power section (N_A active and r redundant amplifiers).

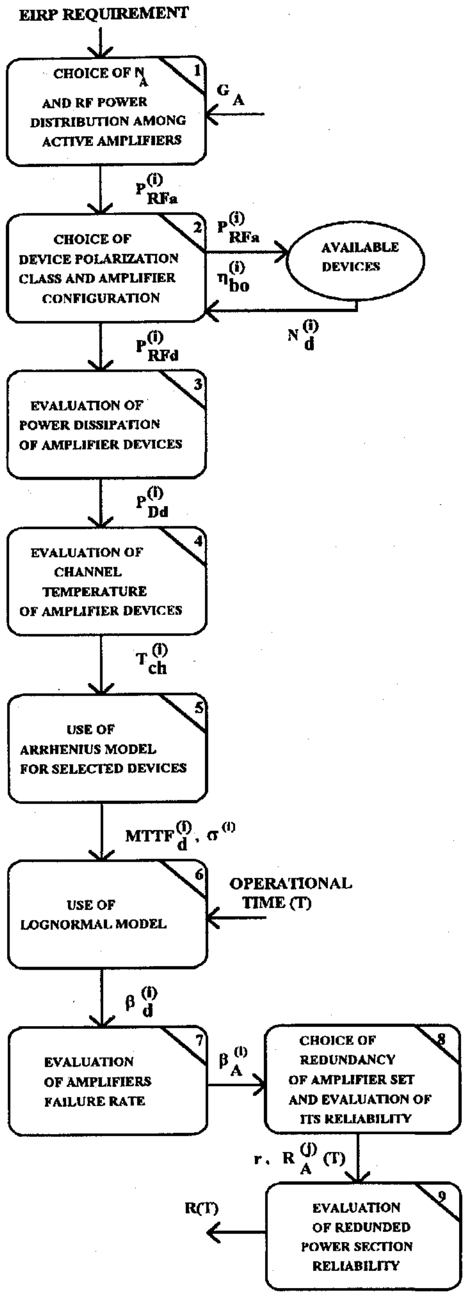

Fig. 3 Steps in the reliability–EIRP relationship modeling.

standpoint and, hence, obtaining the overall reliability as the product of the reliability values achieved from each block,

$$R(t) = \prod_{j=1}^{N_b} R_A^{(j)}(t) \tag{10}$$

The overall reliability of the power section should also account for the redundancy degree and failure rates of the dc/dc converters, as well as the failure rates of the ancillary components.

The various steps necessary to relate the EIRP requirement to the amplifier device reliability parameters can be obtained by joining the modeling building blocks presented in this section. In Fig. 3 that relationship has been displayed in the form of a block diagram where each box, whose inputs correspond to the outputs of the previous box, represents a step of the proposed modeling. The same symbols as those used in the described formulation have been adopted in the flow chart. From the block-diagram description, it is clear how the proposed modeling approach is strongly oriented to system design. In fact, the power section reliability, provided as output of step 9, may be compared to a given threshold to check the consistency and the effectiveness of the power design from the reliability point of view. A critical review phase of the design choice should follow at this point, eventually concerning also the antenna configuration. In some cases, a further critical review of the power-related requirements should be undertaken.

Application Example

To explore the potential of the described approach in the frame of a meaningful scenario, failure rate and reliability of the power amplifiers have been evaluated starting from EIRP, antenna gain, and transmitter topology of a feasible satellite system.[5,6] In particular, a frequency scanning satellite system for mobile communications at L-band has been selected. That system, whose feasibility study has been committed by the European Space Agency, has reached an advanced design phase, rendering the related design guidelines, the choices in terms of power device technology, and on-board architecture, as well as the system requirements, a meaningful set of input data to the reliability model.[5,6]

In Table 1 some output features of the system feasibility study that are relevant to the reliability model are summarized in a baseline reference case. In particular, the power section is composed of solid-state dual amplifiers, allowing an even distribution of the overall power requirement among the amplifiers. As a consequence, the same values of the model parameters are applicable to all amplifiers, as shown in Table 2. The values in Table 2 are derived both directly from the data in Table 1 and through the application of the model steps 1–4 (cf. Fig. 3). To derive the m_α and q_α parameters, power devices different from those of the original study have been selected, because of the availability of their experimental Arrhenius plots. However, as those devices are not space qualified yet, the failure rates obtained through the analysis are slightly higher than the usual figures provided by space-oriented devices.[5,9] Nonetheless, the reliability values obtained through the model (steps 5–9 in Fig. 3) and summarized in Table 3 are compliant with the performance envisaged for the adopted class of devices.

In addition, to exploit the available Arrhenius plots, in the parametric analysis the same device in harmonic control configuration has been adopted to match all of the rf power requirements, through the use (when necessary) of parallel devices. This choice allows a

Table 1 System parameters (reference case)

	Value or feature
EIRP, dBW	55
G_A, dBi	32
$N_r = N_A$	14
η_0	0.85
Amplifiers power	even
Overall power, W	234.7
$P_{\mathrm{rf}a}^{(i)}$, W	16.8
Redundancy	3:2
C/I, dB	18

Table 2 Model parameters values in the reference case

	Value
r	7
N_b	7
$N_a^{(i)} = N_a$	2
$N_{ar}^{(i)} = N_{ar}$	1
$\eta_{\mathrm{bo}}^{(i)} = \eta_{\mathrm{bo}}$	0.54
$N_d^{(j)} = N_d$	2
$\eta_c^{(i)} = \eta_c$	0.965
$P_{\mathrm{rf}d}^{(i)} = P_{\mathrm{rf}d}$, W	8.7
$P_{Dd}^{(i)} = P_{Dd}$, W	19.32
$R_{\mathrm{ch\text{-}c}}^{(i)} = R_{\mathrm{ch\text{-}c}}$, °C/W	1.6
$T_{\mathrm{ch}}^{(j)} = T_{\mathrm{ch}}$, °C	143.9
$m_\alpha^{(j)} = m_\alpha$, °K	2.1×10^{-4}
$q_\alpha^{(j)} = q_\alpha$, h	−31

Table 3 Model results in the reference case

	Value
$\mathrm{MTTF}_d^{(i)} = \mathrm{MTTF}_d$, h	2.59×10^8
$\sigma^{(i)} = \sigma$	2.6
$\beta_d^{(i)} = \beta_d$ (FIT)	329
$\beta_A^{(i,j)} = \beta_A$ (FIT)	658
$\beta_{\mathrm{isw}}^{(i)} = \beta_{\mathrm{isw}}$ (FIT)	10
$\beta_{\mathrm{osw}}^{(i)} = \beta_{\mathrm{osw}}$ (FIT)	20
$R_A^{(j)}(T) = R_A(T)$	0.991235959
$R(T)$	0.940241335

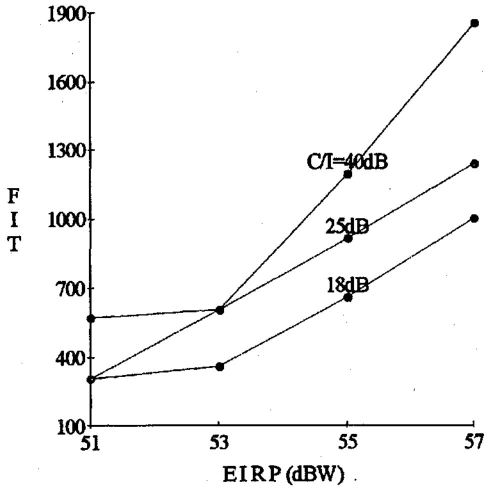

Fig. 4a Amplifier failure rate β_A vs system EIRP and C/I.

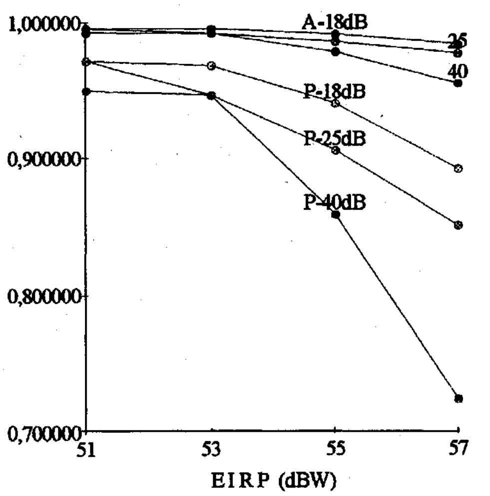

Fig. 4b Block (A) and power section (P) reliability vs system EIRP and C/I with T = 10 years.

very homogeneous analysis, when varying the power demand, at the price of a nonoptimal tradeoff between power and reliability. Finally, it should be mentioned that the model evaluates the amplifiers reliability on a worst-case basis. In fact, the power section and array antenna configurations would allow a graceful degradation of the power performance. However, this potential is not accounted for in the reliability values, which have been referred to the nominal power requirements.

Starting from the reference case in Tables 1–3, the model has been applied to a parametric analysis of the reliability performance. In particular, the failure rate of the amplifiers, the 3:2 block reliability, and the power section reliability have been explored varying the EIRP for various C/I requirements. Results are displayed in Figs. 4a and 4b, assuming $T = 10$ years. In the curves, the smoother slopes, when increasing the EIRP for a given C/I value, correspond to the worsening in the device performance without an increase in the number of parallel devices; the sharper slopes, instead, correspond to changes in both the device performance and the number of devices.

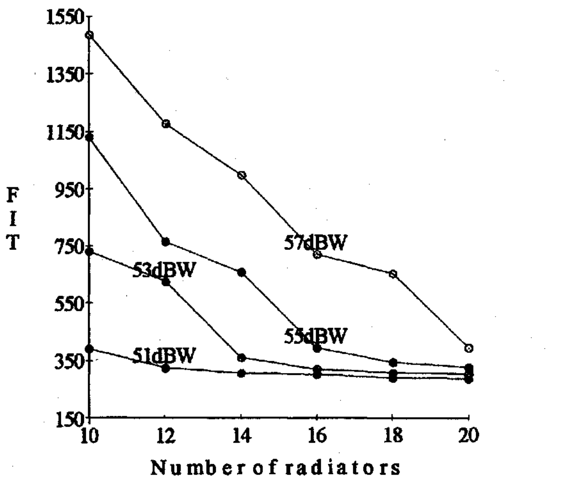

Fig. 5a Amplifier failure β_A rate vs number of antenna radiators and EIRP.

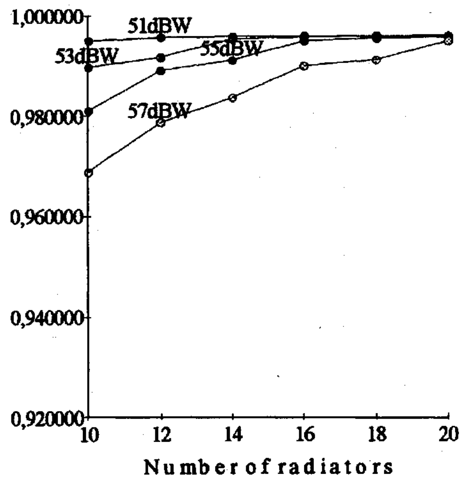

Fig. 5b Block reliability vs number of antenna radiators and EIRP with T = 10 years.

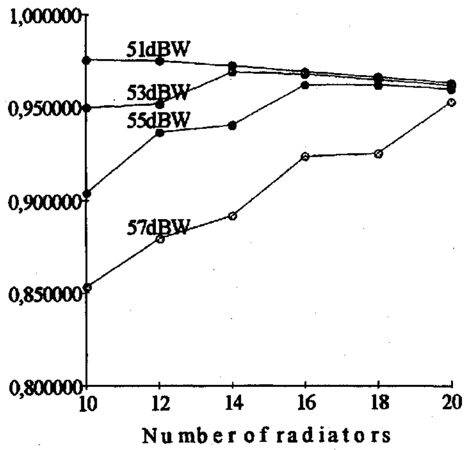

Fig. 5c Power section reliability vs number of antenna radiators and EIRP with T = 10 years.

A further analysis has been performed, evaluating (Figs. 5a–5c) β_A, $R_A(T)$, and $R(T)$, respectively, as a function of the number of antenna radiators N_r, keeping the EIRP as curve parameter. Again, $C/I = 18$ dB and $T = 10$ years are assumed. The changes in slopes are again caused by the variation in the number of parallel devices. In addition, the power section reliability is influenced by the radiator number through both $R_A(T)$ and N_b. As a consequence, for a given EIRP, there is a number of radiators that optimizes $R(T)$: beyond this value, the improvement in $R_A(T)$ when increasing N_r is overcome by the increase in the number of blocks.

Conclusions

An analytical relationship between the on-board power section reliability and the EIRP requirement in satellite communications systems has been derived. The approach is extremely flexible, as it also allows a straightforward relationship between reliability and other system requirements (e.g., C/I) and features (e.g., antenna complexity). This approach is, thus, extremely oriented to a system design environment, where the reliability performance can be considered as a starting design constraint instead of a final checking point in the system analysis.

A realistic satellite scenario has been adopted as an application case, identifying the reliability performance in a wide-range parametric analysis. Many further potential of the model can be exploited: for a given value of the EIRP per channel, the overall EIRP can be related to the number of channels and the bandwidth of satellite systems, hence allowing a direct relationship between reliability parameters and number of channels; the reliability formulation of the power section can be further extended to include hot redundancy modules as well as nonideal stand-by modules.

The major potential of the model dwells in its intrisic capability of changing the design approach of satellite systems: in fact, it offers the analytical opportunity of providing to the reliability performance a key role in the optimization of the whole system design.

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