Analysis of Satellite On-Board Time-Space-Time Switching Networks with Multiple Separated Space Switches

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Summary & Conclusions — Advanced satellite on-board baseband switching processors have Time-Space-Time (T-S-T) structures which are similar to the terrestrial switching networks (Sw-Nw). Generally, the satellite systems require higher reliability than ground equipment because of more severe environment and lack of repair. This paper proposes fault-tolerant satellite on-board T-S-T Sw-Nw with multiple separated space switches instead of a single space switch. We analyze the mean time to unreliable operation (MTUO), as a performance & reliability index for the T-S-T systems with multiple separated space switches as well as conventional T-S-T systems. The MTUO vary depending on the threshold level of blocking-probability and the offered traffic. In general, T-S-T Sw-Nw with multiple space switches have better performance & reliability than those with the single space switch, and their performabilities are appreciably improved, especially for one additional spare space switch. This study can be extended to analyze the performance & reliability of entire satellite communication systems including the on-board baseband Sw-Nw, Rx interfaces, and Tx interfaces.

1. INTRODUCTION

Acronyms

T-S-T time-space-time  
MTUO mean time-to-unreliable-operation  
Rx receiver  
Tx transmitter  
T-SW time-switch  
S-SW space-switch  
Sw-Nw switching network  
OBP on-board baseband processor  
MUX multiplexer  
DMUX demultiplexer.

The present satellite-switched/time division multiple access systems consist of T-S-T Sw-Nw in principle, where T-SW are located in earth stations and S-SW are in on-board transponders. In future advanced satellite systems, regenerative transponders will be designed to switch individual baseband channels in a baseband switchboard in the sky [1-4] with the similar basic functions as terrestrial T-S-T Sw-Nw. This transfer of time stages to satellite transponders can reduce the complex earth segments and can efficiently accommodate various kinds of services.

On-board Sw-Nw require higher reliability standards compared with terrestrial Sw-Nw, because satellite Sw-Nw are usually operated in more severe space environment and are non repairable. If a T-S-T type switchboard has typically a single S-SW, the failure of this S-SW can cause a total failure of the satellite communication links. This problem can be overcome in terrestrial Sw-Nw by redundancy of critical subsystems and repair. However, the situation is different in the satellite systems because of weight limitations on payload systems.

System reliability requirements are usually specified without performance objectives. However, in many telecommunication networks, a failure of a component can cause degraded performance rather than unreliability. In this case, the performance & reliability need to be analyzed jointly. Several quantitative measures such as computation reliability, mean computation before failure, and performability have been used to analyze computer systems, satellite systems, and telecommunication systems [5-8].

This paper proposes more fault tolerant T-S-T Sw-Nw where the S-SW unit (of size N×N conventionally), is separated into two ½N×½N or four ¼N×¼N S-SW including additional interfaces for multiple separated S-SW. We analyze the performance & reliability of Sw-Nw in terms of MTUO.

Section 2 describes a general structure of on-board baseband processor which consists of a baseband T-S-T Sw-Nw. Section 3 explains T-S-T Sw-Nw with a single N×N S-SW and multiple S-SW. Section 4 introduces a combined measure of performance & reliability, MTUO, viz., elapsed time before the system degrades to the extent of given system throughput expressed in terms of blocking probability. The system states are defined and the blocking probability of each state is obtained. MTUO is derived from the stochastic transitional probability matrix. Section 5 evaluates MTUO of the on-board switch for various failure rates of S-SW.

Notation

\[ \theta \]  
threshold of the performance index, \( 0 \leq \theta \leq 1 \)

\[ R(\theta,t) \]  
Pr{system-performance index > \theta until time t|system is in fault-free state at time 0}

\[ N \]  
total number of input/output ports

\[ M \]  
number of S-SW

\[ \eta \]  
\( N/M \)

\[ \lambda_s \]  
failure rate of a S-SW
At state \((i,j)\) of the network, the blocking probability is 

\[ B(i,j) = \frac{1}{T_p(i,j)} \]

where 

- \(T_p(i,j)\) is the threshold of blocking probability 
- \(T_p(i,j) = \frac{n_i}{n_i + \lambda_i}\)

The total offered traffic in Erlang at state \((i,j)\) is 

\[ \lambda_{iM} \]

The effective rate of incoming and outgoing T-SW is 

\[ \lambda_{iM} = \frac{n_i}{M} \]

The channel utilization in state \((i,j)\) is 

\[ a_{i,j}, a'_{i,j} \]

The failure rate of incoming and outgoing T-SW is 

\[ q_{i,j} \]

The effective failure rate of the \(i\) out of \(M\) S-SW and \(j\) out of \(N\) T-SW is 

\[ \frac{1}{T_i} \]

The failure rate of the \(i\) out of \(M\) S-SW and \(j\) out of \(N\) T-SW is 

\[ \phi \]

If one S-SW becomes inoperable due to failure, then total traffic is carried by the other normal one. Figure 2 illustrates a T-S-T Sw-Nw with 4 separated S-SW including additional MUX & DMUX. One fourth of the time slots of each T-SW are connected to one of the separated S-SW. The operation is similar to that of the system with 

\[ \frac{1}{2} N \times \frac{1}{2} N \]

S-SW.
3. The offered traffic is equally distributed.
4. Symmetric path searches are done.
5. The incoming T-SW #i and outgoing T-SW #i are located in one subsystem.
6. Idle incoming & outgoing time slots can be found in normal operation mode of incoming & outgoing T-SW, unless the offered traffic per time slot is 1.0 Erlang.

Huslende [9] introduced the performance reliability index in degradable systems:

\[ R(\theta, t) = \Pr\{H(t) > \theta, \text{for all } t < t\} \]

\[ H(t) = \text{system parameter at time } t \text{ (} t > 0; H(0) = 1, 0 \leq H(t) \leq 1. \]

With \( R(\theta, t) \) known, then:

\[ \text{MTUO} = \int_0^\infty R(\theta, t) \, dt. \]

To analyze the on-board T-S-T Sw-Nw with multiple separated S-SW, we make the following additional assumptions about the system.

\[ R(B_{th}, t) = \Pr\{B(i,j) < B_{th}\}. \]

Figure 5. State Transition-Rate Diagram

Figure 6. Linear Probability Graph

**Assumptions**

7. There is a gracefully-degradable satellite on-board system.
8. There are \( N \) incoming/outgoing T-SW with \( T_i \) time slots.
9. There are \( M \) separated \( \eta \times \eta \) S-SW.
10. Figure 5 shows the state transition diagram.
11. The system is non-repairable (because of its location in the sky).

To evaluate \( B(i,j) \), draw a linear probability graph of state \((i,j)\) as shown in figure 6. Each separated S-SW handles \( T_i/M \) time slots. The number of routes between two T-SW in state \((i,j)\) is \( \psi(i,j) \). For this system:

\[ a_{i,j} = \Pr\{\text{link #1 is busy in state } (i,j)\} \]

\[ a'_{i,j} = \Pr\{\text{link #2 is busy in state } (i,j)\text{ corresponding link #1 is idle}\}. \]

Divide the 'total carried traffic in Erlang' by the 'number of total available channels':

\[ a_{i,j} = T \cdot \bar{B}(i,j)/[j \cdot \psi(i,j)], \]

\[ T = \text{total offered traffic in Erlang}. \]

On the other hand, \( a'_{i,j} \) depends on the event: corresponding link #1 is idle. Use the symmetric path-searching algorithm to get:

\[ a'_{i,j} = a_{i,j} \cdot (1 - 1/j). \]

Search all the available \( \psi(i,j) \) time slots in state \((i,j)\):

\[ B(i,j) = [1 - a_{i,j} a'_{i,j}] \psi(i,j). \]

We introduce a system reliability function: probability that the blocking probability of the system is less than \( B_{th} \) at time \( t \):

\[ R(B_{th}, t) = \sum_{i,j: B(i,j) < B_{th}} P_{i,j}(t). \]

Thus,

\[ \text{MTUO} = \int_0^\infty R(B_{th}, t) \, dt. \]

Alternatively, we can calculate MTUO easily by defining a state \((i,j)\) of \( B(i,j) \geq B_{th} \) as an absorbing state and using the stochastic transitional probability matrix method [10].

To improve the performability of the system, consider a hot stand-by spare S-SW. The total number of S-SW becomes \( M+1 \) and the initially fault-free state is state \((M+1, N)\). To obtain \( R(B_{th}, t) \), first evaluate,

\[ P_{i,j}(t), 0 \leq i \leq M+1, 0 \leq j \leq N \]

from the state transition diagram in which,

\[ \text{state}(M+1,j), 0 \leq j \leq N, \]

are newly added. Even though new states are generated as described here, we still have,

\[ B(M+1,j) = B(M,j), 0 \leq j \leq N. \]
5. NUMERICAL EXAMPLES

We now evaluate numerical examples for the three types of S-SW:

\[ M = 1, \ M = 2, \ M = 4. \]

Given

\[ \lambda_{s1} = 30 \times 10^{-6} \text{ failures/hour} = 30 \text{ kFit}, \]
\[ \lambda_{s} = 10 \times 10^{-6} \text{ failures/hour} = 10 \text{ kFit}, \]
\[ N = 8, \]
\[ T_c = 256, \]

4 special cases (see figures 7 & 8):

\[ B_{th} = 0.1, \ 0.3 \]
\[ \lambda_{s1} = 2\lambda_{s2} = 4\lambda_{s4}, \]
\[ \lambda_{s1} = 3\lambda_{s2} = 9\lambda_{s4}. \]

Calculate MTUO.

![Graph of MTUO vs Average Offered Load with Bth = 0.1 and Bth = 0.3]

\[ o \text{ is for } N \times N \]
\[ + \text{ is for } \frac{1}{2}N \times \frac{1}{2}N \]
\[ \times \text{ is for } \frac{1}{4}N \times \frac{1}{4}N \]
\[ [\lambda_{s1} = 2\lambda_{s2} = 4\lambda_{s4}] \]

Figure 7. MTUO vs Average Offered Load

![Graph of MTUO vs Average Offered Load with Bth = 0.1 and Bth = 0.3]

\[ o \text{ is for } N \times N \]
\[ + \text{ is for } \frac{1}{2}N \times \frac{1}{2}N \]
\[ \times \text{ is for } \frac{1}{4}N \times \frac{1}{4}N \]
\[ [\lambda_{s1} = 3\lambda_{s2} = 9\lambda_{s4}, \text{ with 1 spare S-SW}] \]

Figure 8. MTUO vs Average Offered Load

![Graph of MTUO vs Average Offered Load with Bth = 0.1 and Bth = 0.3]

\[ o \text{ is for } N \times N \]
\[ + \text{ is for } \frac{1}{2}N \times \frac{1}{2}N \]
\[ \times \text{ is for } \frac{1}{4}N \times \frac{1}{4}N \]

Figure 9. MTUO vs Average Offered Load
Figures 7 & 8 illustrate the results. MTUO tends to increase as $h_a$ increases. If the failure rates of multiple separated S-SW, $\lambda_{g2}$ & $\lambda_{g4}$, become much smaller than $\lambda_{g1}$, the MTUO becomes better. System reliability can be appreciably improved by adding 1 spare S-SW to these three types of S-SW. Figure 9 (corresponding to figure 7) shows the result.

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REFERENCES


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