Tools and Methods for System of Systems Applications in Telecommunication Networks[1]

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Abstract. This Ph.D. Thesis discusses the System of Systems (SoS) concept adjustment into information and communication technology (ICT) relative fields. The research objective of this Ph.D. thesis is to provide new methods and tools in ICT related enterprises and professionals, aiming into proper analysis and modelling of telecommunications networks. This will enhance the current methodologies and frameworks to battle current challenges such as increased complexity, scaling and uncertainty without of course following a static concept analysis. Pilot studies over a variety of ICT subjects also conducted in order to verify validity and cogency over the developed tools and methods.

Keywords. System of Systems, Reliability, Optimization, Adaptation, Emergence, Reconfiguration

1 Dissertation Summary

1.1 Introduction

Recently a significant interest was observed in the field of System of Systems. Particular attention has been paid on System of Systems Engineering which deals with the development of tools, methods and solutions to the challenges of System of Systems. Nevertheless, for better understanding a SoS, one needs to clarify the characteristics that should be included in it. A System of Systems should consist of a number of operationally and managerially independent systems. The individual systems should be autonomous that is to perform a standalone operation. On the other hand, the independent systems should be integrated in a higher level system (meta-system) to perform

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[1] Dissertation Advisor: Dimitris Varoutas, Assistant Professor

a mission / purpose for which each member plays an integral role. Another main feature of System of Systems is that it is a complex system and as such exhibits a dynamic and emergent behavior. Finally, the System of Systems is a dynamic entity as new systems are added and current systems are replaced or removed. In the following sub chapters of the dissertation summary, some pilot networks were SoS concept was exercised will be presented. In detail, the constituent systems of the SoS meta-system will be denoted while outlining the major characteristics of the System of System Engineering theory. For each one of these pilot networks a method/tool was researched and developed in order to enhance knowledge of the SoS while confronting uncertainty. Results on each research study are presented and various details are also disclosed.

1.2 Reliability Study using System of Systems concept.

Service continuity is becoming a critical path for the delivered quality of service (QoS) [1]. Towards this end, telecommunication companies are continuously investing in research and development for reliability analysis. However, the provision of uninterrupted services that require high bandwidth and interactivity often leads to increased complexity of telecommunication systems. This converts the new generation of telecommunications networks into "Systems of Systems"[2], [3], consisting of a mixture of software, hardware and human intervention. The starting point for the development of a new method/tool is to identify its requirements. The System of Systems method/tool should primarily address the high complexity, the large size as well as the dynamic and emergent behavior of telecommunication network. Moreover, it needs to be flexible in order to incorporate and evaluate the impact of unknown events. Following these guidelines, this Ph.D. thesis proposed a new SoS framework[4] for the reliability assessment of telecommunication networks. The proposed framework is a combination of the analytical method of Hazard and Operability Analysis (HAZOP)[5], [6] with the mathematical representation of Fault Tree Analysis (FTA)[7], [8] along with the directed acyclic graphs (DAG) of Bayesian networks (BN)[9]–[11]. In addition, this method encapsulates sensitivity analysis techniques (Monte Carlo Simulations)[8] in order to quantitatively evaluate the impact of unknown risks and events such as the addition of new systems with unknown characteristics. In order to further reveal real SoS behaviors (e.g. evolution – emergent behavior of SoS), exploratory modeling is implemented. The telecommunication network under investigation is a fiber to the curb (FTTC) access network based on VDSL technology (**Fig. 1**). The network has five independent systems. The Customer Premises Equipment (CPE), the Digital Subscriber Line Access Multiplexer (DSLAM), the Local Exchange (LE), the Central Office (CO) and the Broadband Remote Access Server (BBRAS).

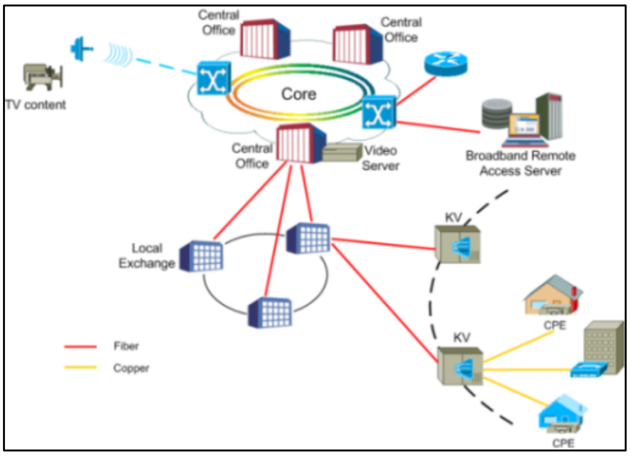

Fig. 1. System under investigation

1.3 Results and Discussion over Reliability Study using SoS.

The input parameters of the obtained model is the exposure time T and the failure rate λ that is the inverse of the mean time between failures (MTBF). In this study, the exposure time T considered arbitrarily as 10 years. However, any other value of the exposure time can be easily introduced in the proposed framework. The mean time between failures (MTBF) that were used in the present study, have been mined from the database of a build in techno-economic tool containing numerous network components [1].Probability of Failure of each system is then estimated (**Fig. 2**). Apart from the Probability of Failure, several importance metrics can also be derived through FTA analysis. Moreover, in order to incorporate complex and unknown events as well as to extract useful guidelines, one should resort to Bayesian network models. Such models will provide us the asset of answering complex probabilistic queries about the network operation, using the information about nodes and interfaces obtained from the HAZOP and FTA analyses.

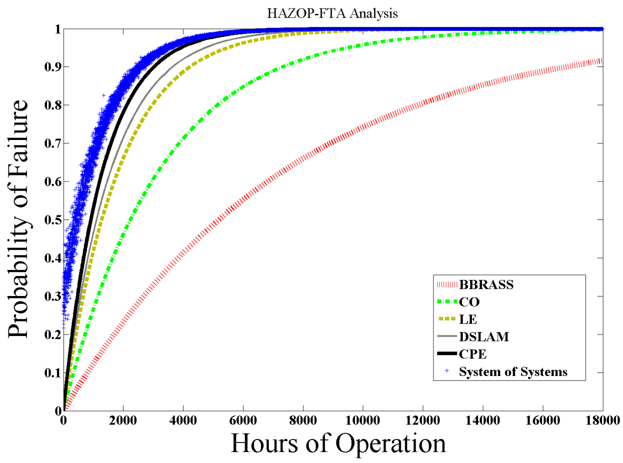

Fig. 2. Probability of failure of the SoS constituent systems for 18000 hours of operation

The inclusion of Bayesian Networks in the Framework of the study makes feasible the generation of quantitative results that deal with complex and unknown events. This way deep uncertainty is also modeled through the proposed Framework. Bayesian Network parameters are actually embedded over the Conditional Probability Tables (CPTs) of each system. Using the BN of each SoS representation, several conditional probabilities can be calculated such as the probability of failure of the SoS given that LE is failing as follows (Eq.1).

$$P\left(SoS = True \mid CPE, DSLAM, LE = True, CO, BRASS\right) = \\ = \frac{\sum_{C,D,CO,B \in [True, False]} P\left(SoS = T, C, D, L = T, CO, B\right)}{\sum_{SoS,C,D,CO,B \in [True, False]} P\left(SoS, C, D, L = T, CO, B\right)} \quad (1)$$
[2]

In order to further study the emergent behavior of the SoS under investigation, one should resort to techniques dealing with large degrees of uncer-

[2] Where CPE, DSLAM, LE, CO, BBRASS, True and False are written as C, D, L, CO, B, T and F for simplicity.

tainty (deep uncertainty). Under conditions of deep uncertainty, it is hard to forecast the realizations and the time-varying relationships of relevant factors in the SoS. Furthermore, these situations of uncertainty can be occurred in a system that has not yet existed. The latter case is examined in this subsection since new versions of the SoS can be obtained through the addition/deletion/replacement of systems or links. Unfortunately, in deep uncertainty the appropriate conceptual models to describe interactions among SoS variables as well as the probability distributions to represent uncertainty about key parameters in the models are unknown. The numerical simulations include evaluations of model outcomes across a large set of possible SoS representations. Each plausible SoS representation can be assumed as one hypothesis about SoS behavior. By investigating a large set of such hypotheses and by evaluating their correctness, the “whole picture” of SoS emergent behavior can be obtained. A simple method to construct the possible SoS models is to include time in the model specification defining the evolution of the SoS model. The evolutionary modeling of SoS is depicted in **Fig. 3**.

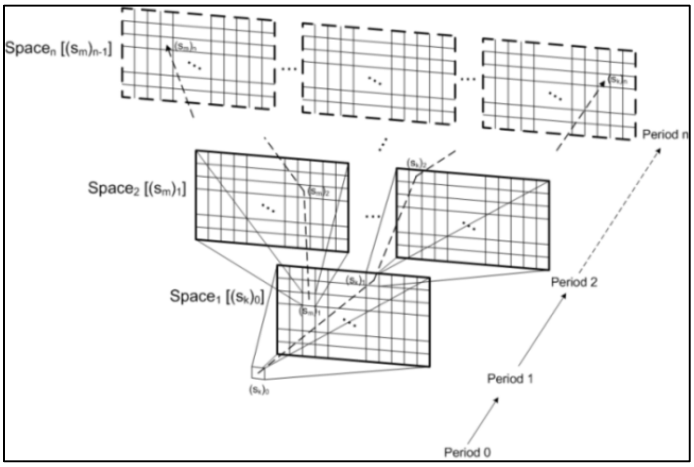

Fig. 3. Network Realization along with Uncertainty spaces

As shown in **Fig. 3**, there is a dependence of uncertainty spaces in a period i on the realizations of all the preceding periods. For example in Period 2, the uncertainty space ($Space_2\ [(s_m)_1]$) is generated from the realization $(s_m)_1$ of the preceding uncertainty space ($Space_1\ [(s_k)_0]$) which in turn is originated from the initial condition $(s_k)_0$. Hence, a possible future path (dashed lines) can be represented by the sequence $(s_k)_0 \rightarrow (s_k)_1 \rightarrow (s_k)_2 \ldots \rightarrow (s_k)_n$. In **Fig. 4**,the uncertainty space 2 (after four years) originating from the realization[3] (80% $\lambda_{1,in}$,110 % $\lambda_{2,in}$, 0.3, 0.5) of the previous period (2 years) is illustrated as a color map where different colors correspond to different probability values estimated using (Eq.2).

$$P(SoS = True|CPE = False, DSLAM, LE, CO, BRASS) = \frac{\sum_{D,L,CO,B \in [True,False]} P(SoS = T, C = F, D, L, CO, B)}{\sum_{sos,D,L,CO,B \in [True,False]} P(SoS, C = F, D, L, CO, B)} \quad (2)$$

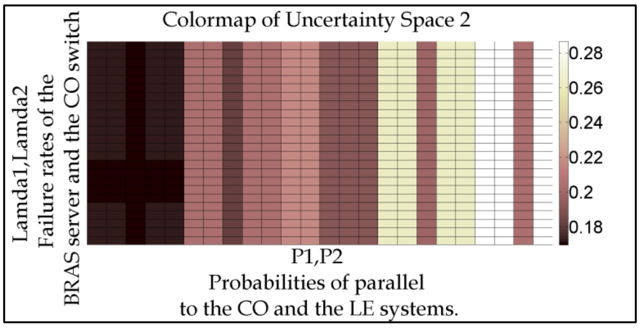

Fig. 4. One of the possible SoS representations after four years (period 2).

In order to simplify **Fig. 4**, the coordinates of each realization are omitted. However, a method to determine the coordinates of a realization *k* (*i*-th line and *j*-th column of **Fig. 4**, is provided by the following equations.

$$\lambda_{1,k} = \lambda_1\left(\left\lfloor \frac{i-1}{5} \right\rfloor + 1\right) \quad (3)$$

$$\lambda_{2,k} = \lambda_2\left(\mathrm{mod}\left((i-1),5\right)+1\right) \quad (4)$$

$$P_{1,k} = P_1\left(\left\lfloor \frac{j-1}{5} \right\rfloor + 1\right) \quad (5)$$

$$P_{2,k} = P_2\left(\mathrm{mod}\left((j-1),5\right)+1\right) \quad (6)$$

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3 The values for the parameters λ1, λ2, P1, P2 are from CPTs, where $\lambda_{i,in}$ are the original values of the component's failure rate used in the current research.

where $\lfloor x \rfloor$ denotes the integer part of x and $\lambda_i(m)$, $P_i(m)$ represent the *m*-th entries of λ_i and P_i respectively in CPTs. Using the color map **Fig. 4**, one can predict the impact of possible changes (components replacement and/or addition or deletion of links – systems) in the infrastructure by estimating the values of conditional probabilities and determine the emergent behaviors of the SoS by exploring the corresponding paths.

1.4 Optimization and Management of Complex Telecom Investments using System of Systems concept.

The high importance of Information and Communications Technologies for Europe can be viewed by its action to include Digital Agenda in Europe 2020 Strategy. Telecom operators who are the main investors of telecommunications networks have thus to exploit the funding opportunities from the one hand and deal with the high uncertainty influencing such deployments. Hence accurate, quick choices along with budget details and strategy plans need to be constructed on a clear basis. A quick and accurate methodology scheme that will make investors to enhance current methodologies and decide with greater confidence about critical aspects of their investment should consequently be provided. As telecom investments are difficult to be modelled by traditional systems methodologies, given their space and time scale, their multi-dimensional nature, their complexity, the uncertainties arising from demand and price evolution and the emerging needs of users, new approaches incorporating complexity while keeping computational simplicity are needed. In addition, qualitative issues such as the first movement advantage and externalities deriving from the associated networked economies are even more difficult to be incorporated in a simple and accurate manner. Earlier approaches to implement the SoS concept in a techno-economic problem for telecom networks providing a complete and accurate reference to telecom operators and policy makers can be found in [12]. Although this work managed to address the emerging behavior of telecom investments, it could not deal with the complex interdependencies of the constituent systems as well as the externalities arising from the associated networked economies. In this Ph.D. thesis, a methodology based on System of Systems (SoS) framework[13] proposed for modeling telecom investments and defining strategies leading to profitability under several constraints. Adaptation and reconfiguration concepts on initial decided strategies are also encapsulated in this framework. Having a compact and almost closed-form nature, the proposed framework can be proved an extremely valuable tool for telecom operators. As shown in **Fig. 5**, there are five interdependent systems. The Competitor Analysis (CA), Budget Allocation (BU), Capital and Operational expenses (CAPEX + OPEX), Demand Forecast (DE) and Network Externalities (NE). It should be noted that all the constituent systems are able to interact with each other. In this study, the dependence of customers' number on external factors such as price is incorporated in network externalities system. This, along with the rest systems, will define the expected revenues of the network.

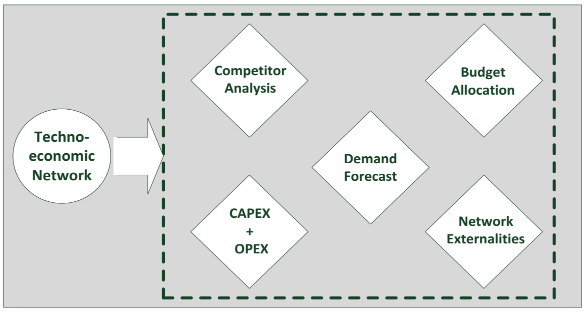


Fig. 5. Techno-economic Network under investigation, typical representation

1.5 Results and Discussion over Techno-economic Study using SoS

FTTH architecture for the last mile is investigated as a case study of the proposed framework. The area is described in terms of subscriber density and geographical characteristics. The area model chosen corresponds to a dense urban area with a surface of 12 km^2 and 5,641 customers per km^2. It is assumed that there is one central office, serving 65,536 customers in total. The total available budget is assumed to be 35M€ for the whole study period of 10 years maximum. The starting year of operator's investment will be decided by the optimization process using genetic algorithms (GAs)[14]. In order to avoid trapping on local extrema, the GA is running 1000 times. In order to maximize provider's profit at the end of the study period, the following nonlinear programming problem is stated following the objective Function as in the indicative equation (Eq.7). Using the estimated parameters along with constituent systems' mathematical models, an optimum strategy for the incremental network deployment (dynamic budget allocation) leading to profit maximization at the end of the study period will be investigated and proposed. The nonlinear programming (NLP) problem is solved using a GA and implemented in Matlab.

Maximize objective Function H(x).

Subject to :

Incentives

Budget

Subscribers

Pricing Complicate Model

Variables: (7)

X0, Starting Year of Investment

X1, X2 competitors entrance case analysis

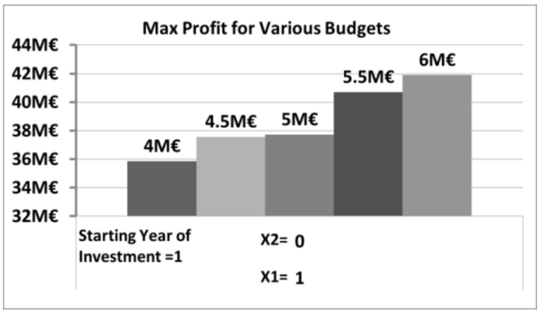
X3..X12 ,each year of the total 10 of study, for yearly service pricing

Contraints: $1 \leqslant X0 \leqslant 10$

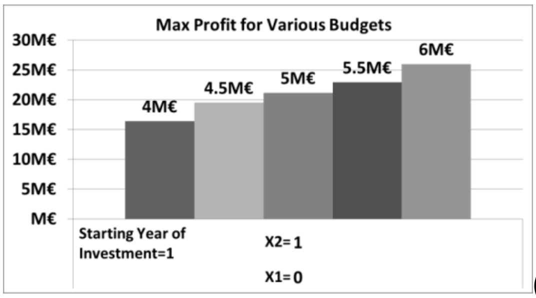
$0 \leqslant X1, X2 \leqslant 1$

$X3 \leqslant X4 \ldots X11 \leqslant X12$

From the derived results, it is deduced that in almost 90% of the cases the FTTH investment is started in the first two years. This is somehow expected and can be attributed to the longer network's operation period leading to increased revenues and thus profits. A profitability of ~100 M€ is observed in the majority of the simulation runs. Another interesting result is that in more than half of the 1000 cases, the operator decides to invest before his competitor. This can be mainly explained by the extra benefits (incentives) received by the first investor. In these cases, a maximum profit of 103 M€ is observed. Moreover, a delayed decision (invest after the competitor) results in significant profit losses. An interesting case is the simultaneous investment of both operators which is the second best choice as the profitability remains in good levels. One more interesting point is that in the majority of cases where we have a significant profit over the years of study, profitability is observed after the fourth year. The available total budget is a point of great debated and should be further investigated. Towards this direction, a series of simulation runs were performed assuming -20%, -10%, 10% and 20% budget change respectively. The obtained results are illustrated in **Fig. 6**(a) and **Fig. 6**(b). It is straightforward to understand that a bigger amount of budget is required to further expand the network, needed to meet the high demand due to price reduction policy that was followed. In the analysis of the previous sections, it is assumed that the profits of the investment are shared to the shareholders of the operator's company. However, this strategy is proved to be the worst in terms of available budget. In order to investigate the impact of partial profit re-investment on both the required available budget and the viability of the project, eq. (8) must be transformed to the following form. Assuming an available budget of 25 M€, a series of optimization runs are performed again.



(a)



(b)

Fig. 6. (A) Pivot Chart showing Maximum Profit when Starting at Year 1, <u>BEFORE</u> Competitor for Various Budgets (B) Pivot Chart showing Maximum Profit when Starting at Year 1, <u>AFTER</u> Competitor for Various Budgets

$$\sum_i^{years} Bi \leq \text{BUTotal} + \sum_i^{years} (A\,\%) * Profit \qquad (8)$$

A= [30, 50]

From the obtained results, it is deduced that, the maximum profit (around 93 M€) is achieved by re-investing 50% of the annual profit in network extensions besides the small amount of available budget. The case of starting the investment after competitor is also studied and it produces really low profits. This is a high risk case since if the operator under study misses the investment entrance, a severe amount of money for budgeting will be needed in order to gain market share capable of providing adequate profits.

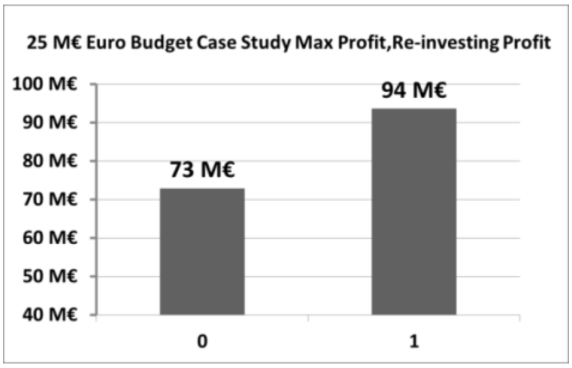


Fig. 7. : Maximum Profit of investment with 25 M€ budget. Starting year of investment is 1. X=0 equals to after competition investing, and X=1 equals to start investing before competition. Assuming aggressive investment in network construction of yearly profits.

In order to compare the results derived with and without re-investment, a series of optimization runs are also performed using eq. (8). The maximum profit was ~70 M€, which is much lower than the case of profit reinvestment. This can be easily explained by the fact that low available budget results in limited network deployment. Thus, the growing demand cannot be met by keeping the number of subscribers in low levels. It should also be highlighted that the same conclusions are derived following the advantageous strategies of pricing policy and investment entrance. This is a clear indication that telecom investments are not static procedures. Contrary, more complicated strategies and adaptive policies should be adopted. This is of high importance, especially in cases where the initial targets are missed over the study period. In order to address such emergent behaviors of the SoS under investigation, it is thus crucial to continuously monitor the defined metrics of effectiveness and performance of a successful investment. Interventions, in terms of pricing policy or percentage of re-investment, deviating from the initial plan should be performed in order to keep profitability in the desired levels.

2 Conclusions

This thesis and the relative published research material[4] contribute in the reliability study field using the SoS methodology concept with the following:

- All type of risks/hazards covered thru the combination of reliability analyses.
- Enables dynamic characteristics in the proposed reliability analysis Framework, through the Exploratory Modelling as an emergent need of complex systems analysis. Meanwhile with the specific modelling encapsulation the reconfiguration risk/hazard is revealed as part of the emergence of the complex networks analysis.
- Both qualitative and quantitative approach.
- Inclusion of Uncertainty Space in the proposed Reliability Analysis, by using sensitivity analyses. Purpose is to ensure unknown events are taken into account over the cluster of residual mishap risk.

The proposed methodology can be used for evaluation of network performance and monitoring of service quality and service level agreements (SLAs) in a telecommunication network. It can also be exploited in techno-economic studies in order to evaluate the cost of operation, administration and maintenance (OAM). Additionally, in the techno-economics field, this Ph.D. thesis and the relative published material[13] contribute in the specific field the below outlined items:

- Multiple Representation Scenarios of the telecom investment.
- Exhaustive search and strategy alignment based on each case specific action needs and.
- The Optimization Study is also capable for reconfiguration towards decision making enhancement (market or technology related).
- Encapsulation for Dynamic Budget Allocation and Re-investment scenario.

The above mentioned contributions are part of generic methods and tools targeting also over a general Framework. This enables the usage of the developed methods in various fields that are directly related to complexity. Some examples that could follow the SoS engineering theory are the Information Systems (IS) and Smart Cities. Both, belong to the author's future research fields in line with the implementation of the SoS methods/tools developed as part of this research effort.

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