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Optimization/simulation-based risk mitigation in resilient green communication networks

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ABSTRACT

This paper proposes a solution to the trade-off between energy-efficiency and resilience in communication networks, where the energy profiles express the decreasing return to scale effect. Risk engineering is used as a basis to provide the risk mitigation framework defining various trade-off strategies (risk minimization, total benefit coverage, cost balance, and profit maximization). As obtaining the exact solution to the assumed trade-off strategy with an analytical or purely optimization approach is impossible in practice, an original method combining iterative optimization procedures with simulations providing updated values to feed the optimization model is proposed to find a satisfactory risk mitigation option. A numerical example is presented to show the performance of the proposed method.

1. Introduction

To countermeasure losses stemming from node or link failures in communication networks, automatic *recovery methods* are designed by the network management plane. The recovery methods operate in various ways (at different technological layers, with various levels of sharing, scope, etc.), and result in different quality parameters, such as availability, recovery time, robustness to multiple failures, etc. (Chołda et al., 2007; Chołda and Jajszczyk, 2010). They also incur various levels of cost, since in order to bypass affected elements, it is necessary to use *backup* resources. In this paper, we focus on one of the most prominent operational costs at present: energy usage. As such, we deal with the dimensioning of (*a*) *resilient* (i.e., survivable to failures) and (*b*) *green* (energy-efficient) communication network topologies. While the former is one of the main non-functional requirements in today's networks, where large transmission pipes carry high volumes of traffic which should not be interrupted, the latter is a relatively new problem that needs to be addressed for a range of reasons from the business viewpoint (Aleksić, 2013):

- a lot of energy is consumed by communication networks (approximately 3% of all the world's energy) and the energy costs are high;
- if energy usage is too high, its supply can simply be cut off; this effect can replace today's capacity with energy as a future bottleneck in network management and operation (Bolla et al., 2011a);
- regulator pressure on the industry to protect the environment may lead to the introduction of energy saving policies that should be addressed by network operators.

There are three options for the operation of devices with respect to energy management procedures (Perelló et al., 2013; Quittek et al., 2013):

- active mode (fully used): at each time point, the device can operate at full capacity;
- *sleep mode* (low power/standby/idle/hibernation): the device is using some energy and can switch to active mode almost instantaneously;
- switched off mode (inactive): the device is not using any energy, and it takes some considerable time for the device to be woken up.

While the difference between the last two modes is important in traffic engineering, here we are interested in network dimensioning (long-term behavior), and we identify the sleep mode with switching off. We follow Jirattigalachote et al. (2011) who assume that both idle and inactive modes consume almost zero energy. While sleep mode mechanisms are generally not present in contemporary network devices, some attempts to include them

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in protocol suites exist (Morea et al., 2013). Additionally, in 2009, the Internet Engineering Task Force established a working group on energy management (Eman) to provide the management plane with ontology necessary for presenting data useful in energy-aware networks, taking into account the sleep mode (Quittek et al., 2013; Parello et al., 2015). Perelló et al. (2013) deal with two basic types of sleep modes: link sleep mode (LSM) and optoelectronic device sleep mode (OESM). The latter assumes switching off transponders or regenerators, while the former mainly concerns optical amplifiers. Since the switching on process in OESM can be fast (order of milliseconds), it may be suitable for protection procedures, i.e., proactive recovery methods (Chołda et al., 2007) that are applied in the method presented in our paper. Another aspect relating sleep mode to resilience is stressed by Caria et al. (2012), who list certain drawbacks of this mode, by emphasizing that due to switching off:

- short network instabilities may occur due to the need to redirect traffic; and
- traffic paths are longer, increasing delays, susceptibility to failures, and degrading connectivity.

Therefore, resilience provisioning and aiming to make networks more environmentally friendly ('green') are somewhat contradictory, since energy-efficient routing increases risk levels. Additionally, the introduction of backup resources involves increased energy usage, and thus energy minimization counteracts resilience provisioning. The papers aim to solve the trade-off using engineering approaches. Wiatr et al. (2012); Francois et al. (2014), and Addis et al. (2014) discuss the existence of a trade-off between energy-efficiency and performance, including resilience. Although there is extensive literature that considers the design of energy-efficient networks with resilience provisioning, researchers typically deal with optimization problems from the energy-efficiency minimization viewpoint, considering resilience needs as additional constraints only (Musumeci et al., 2013). From this perspective, it has been shown that energy-efficiency approaches (mainly using sleep modes for spare resources) enable operators to save a significant percentage of energy usage, even with protection methods applied, but the reliability is put in jeopardy with increasing usage of the sleep rate. Therefore, another approach is necessary. Here, following our previous paper (Chołda and Jaglarz, 2015), we propose a *business-oriented risk engineering* umbrella for defining a way of dealing with the energy–risk trade-off. This approach emphasizes the economical perspective and treats the resilience and energy aspects in a single monetary (financial) space. Risk is understood as "an uncertain event or condition that, if it occurs, has a positive or negative effect on an objective" (IEEE, 2004), where each operator's objective is to increase profits and minimize losses. As both are dependent on random events such as failures, risk is described with two basic parameters: *probability* (frequency) and *impact* (severity). Here, we identify impact with the basic network reliability aspect, expressed as the *cumulative downtime* experienced by the connection (demand) over a given period of time. Then, it is expressed in monetary units.

Of all the stages of the risk management cycle, designers of resilient networks will be the most familiar with certain elements of the risk control phase. The task of technical personnel is to prepare solutions that are not dominated from the optimization viewpoint (see Section 2.2.2). Then, on the basis of the options presented and their in-depth description (e.g., with risk quantification), an *informed business decision* is taken by business management. For instance, a network operator will decide what kind of recovery methods should be provided to the clients in order to increase the probability that the Service Level Agreements (SLAs) will not be violated. This approach is known as *risk mitigation*. There are two types of trade-offs that are decided:

- how to select a strategy from a group of possible responses that can be described with the types of factors: cost and changed level of risk; and
- how to use a limited cost budget to deal with different types of resources.

In this paper, we focus on the former approach, as we assume that theoretically the budget (energy usage) is not limited. However, most of the applied risk mitigation strategies tend to limit the budget as the final output. Risk engineering enables us to deal with the mitigation of recognized risks (failures, in our case) traded off with the response costs (energy, in our case). Risk-awareness is a tool providing a better adjustment of recovery methods to a single demand by taking both aspects into account. We use risk management approaches to deal with network dimensioning problems in uncapacitated networks with specific link cost functions.

In the context of risk management in resilient networks, risk assessment is the most popular topic of research. For instance, Vajanapoom and Tipper present a set of papers on the topic, with the most comprehensive (Vajanapoom et al., 2013) presenting linear programming-based models applying the so-called risk exposure, that is the average risk measure. Similarly, (Dikbiyik et al., 2012) present an integer linear program that also bases risk response on risk exposure, where the consequences are based on the cumulative downtime exceeding the assumed threshold. Gonzalez and Helvik (2012) provide a set of optimization approaches using two-stage stochastic programs to increase the provider's gain (to minimize recovered connection costs and penalties paid for faults incurred). However, unlike the mentioned prevailing optimization problems defined in contemporary resilient networks, we would like to find a computationally effective method of optimizing assignment of recovery options constituting risk mitigation. We do not believe it can be done by a sole big static optimization problem as done in the works published before. Even though it may be theoretically possible to formulate a large optimization problem that finds the risk mitigation solution, in practice: (*a*) it is not possible, since typically we do not have initial data to feed such a model, and the data is obtained during flow assignment simulations; (*b*) we either are not able do provide exact analytical results predicting the behavior of a network where various demands use different recovery options (e.g., sharing of resources) and non-additive risk measures are applied, or the elaborated methods are strongly non-linear and thus not useful in mathematical optimization; (*c*) the mix of various service classes is difficult to treat in a single network setting. Instead, we propose a method that combines optimization iteratively with simulations based on this optimization results. The simulations are used to provide updated values of constants feeding the optimization model in the next iteration. Then, we are able to obtain convergence of the optimization process with the relevant output. As checked with various network cases, the speed of the convergence is satisfactory from the standpoint of the management plane operation.

The remainder of the paper is organized as follows. First, to show the context of our work, we discuss related state-of-the-art in Section 2. Section 2.1 presents an overview of the design of green networks, with a focus on the most typical energy profiles used in our studies. Section 2.2 outlines the main concept behind solving the intrinsic trade-off between energy-efficiency and resilience provisioning. This is based on risk management, mainly its step known as risk response, where we focus on business-relevant selection of countermeasures to failures (i.e.,

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