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Probabilistic region failure-aware data center network and content placement☆

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ABSTRACT

Data center network (DCN) and content placement with the consideration of potential large-scale region failure is critical to minimize the DCN loss and disruptions under such catastrophic scenario. This paper considers the optimal placement of DCN and content for DCN failure probability minimization against a region failure. Given a network for DCN placement, a general probabilistic region failure model is adopted to capture the key features of a region failure and to determine the failure probability of a node/link in the network under the region failure. We then propose a general grid partition-based scheme to flexibly define the global nonuniform distribution of potential region failure in terms of its occurring probability and intensity. Such grid partition scheme also helps us to evaluate the vulnerability of a given network under a region failure and thus to create a "vulnerability map" for DCN and content placement in the network. With the help of the "vulnerability map", we further develop an integer linear program (ILP)-based theoretical framework to identify the optimal placement of DCN and content, which leads to the minimum DCN failure probability against a region failure. A heuristic is also suggested to make the overall placement problem more scalable for large-scale networks. Finally, an example and extensive numerical results are provided to illustrate the proposed DCN and content placement.

1. Introduction

Data center networks (DCNs), which consist of hundreds or even thousands of servers and massive storage resources, are becoming increasingly important infrastructures to support the wide spreading cloud computing services [1,2]. In general, DCN design involves the issues of DCN and content placement, path and content/service protection, QoS guarantee, etc. This paper focuses on the DCN and content placement. The DCN placement can be roughly divided into two categories, to place the components of a DCN at different nodes of a given network [3], or to place multiple DCNs at different nodes of a given network [4,5]. This paper concerns the latter.

It is notable that DCNs are facing more and more potential large-scale disaster threats, both natural and human-made. Some recent major network disruptions due to disasters include 2012 Sandy Hurricane, 2011 Japan Tsunami, 2008 China Wenchuan earthquake, etc. [6–12]. Such disasters usually affect a specific geographical region, causing failures of a set of network components and degradations or even breakdowns of vital network services [13]. For instance, China Wenchuan earthquake in 2008 leads to the damages of more than 3000 telecom offices and around 30,000 km optic cables [8]. Thus, the study of DCN and content placement with the consideration of region failure is critical for DCN designers to take proactive measures against the region failure in the DCN design phase.

Given a network, the placement of DCN and content in the network with the consideration of potential region failure usually concerns with the following two aspects: (1) to assess the network vulnerability due to a region failure; (2) based on the network vulnerability information, to properly place the DCN and content in the network such that the DCN failure probability due to region failure is minimized. Some works are available on the assessment

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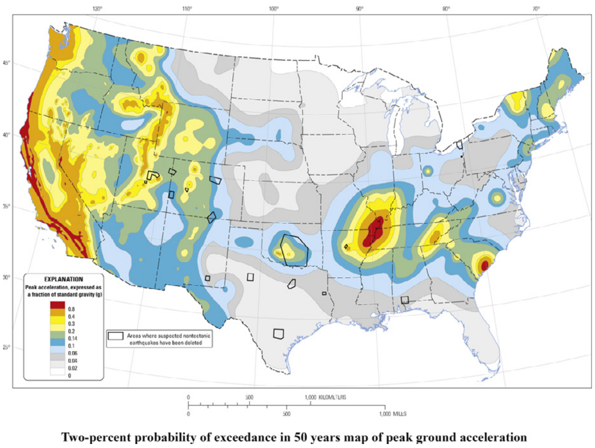

Fig. 1. U.S. national seismic hazard map.

of network vulnerability and identification of vulnerable network zones due to region failure [14–18]. Based on the deterministic circular/line cut region failure models, the network vulnerability assessments are conducted in [14,15]. In [16] and [17], a probabilistic failure model and grid partition based framework are developed to efficiently estimate the network vulnerability. Recently, network vulnerability assessment with the consideration of multiple simultaneous probabilistic failures is investigated in [18]. It is notable that the above works on network vulnerability assessment all assume that both occurring probability and intensity of region failure(s) follow the uniform distribution in the network area. As illustrated in Fig. 1 for U.S. national seismic hazard map [19], we can observe that in the real world, however, a disaster may happen in different areas with different probabilities and different intensities.

Regarding the DCN and content placement with the consideration of potential network failure(s), Xiao et al. [5] study the optimal DCN placement problem with service routing and protection to minimize the network cost, while ensuring fast protection of all services against any single link failure or service failure at a particular DCN. By assuming multiple region failures in fixed locations, the work in [20] concerns with the joint design of content placement, routing, and protection of paths and contents to achieve more efficient protection of optical DCNs than dedicated single-link failure protection, while the work in [21] investigates the DCN and content placement to minimize both the DCN contents unavailability due to DCN hosting nodes damage and requests unreachability due to paths damage from disasters.

Notice that two limitations of above works on DCN and content placement are that they failed to take into account the global nonuniform distribution of potential disasters in terms of their locations and intensities, and they also did not consider the inherent tradeoff between failure probabilities of DCN hosting nodes and failure probabilities of requesting paths (e.g. paths between content requesting nodes and DCN hosting nodes). In a large-scale network there are multiple paths between an arbitrary pair of nodes, which indicates that the probability that these paths simultaneously fail due to disaster is very small. In contrast, if a DCN hosting node fails after disaster, the contents provided by this node will be unavailable and the adverse impact of such failure on the DCN is even greater than the path failure. Thus, the tradeoff between failure probabilities of DCN hosting nodes and failure probabilities of requesting paths should be considered. Also, since content or service providers in DCNs wish to satisfy user demands with low latency, we need to consider the traffic transmission delay issue as well in the DCN design.

To address the above limitations, this paper combines the probabilistic region failure model and grid partition scheme to capture the key features of the general nonuniform distribution of a potential disaster in terms of its location and intensity, and then apply them to conduct the network vulnerability assessment. Based on the vulnerability information of a given network for DCN and content placement, an optimal DCN and content placement scheme is proposed with the consideration of the tradeoff among failure probabilities of DCN hosting nodes, failure probabilities of requesting paths and traffic transmission delay. In our work, DCN placement is static, which is implemented at the network planning stage for only once. However, since the information on disaster and content properties (e.g. content request) is time-varying, content placement can be adjusted when the information on disaster and content properties is updated. In general, content placement can be optimized either periodically according to daily content requests variation, or within the early warning time of an upcoming disaster if the DCN failure risk is observed higher than the current risk evaluation. The main contributions of our work can be summarized as follows.

- We first propose a general grid partition-based scheme to evaluate the vulnerability of a given network due to the global nonuniform distribution of a region failure, in which the probabilistic region failure model is applied to determine the failure probability of a node/link. Then we can create a vulnerability map for DCN and content placement in the network.
- Based on the grid partition-based scheme and the corresponding vulnerability map , we develop an integer linear program (ILP)-based theoretical framework to achieve optimal placement of DCN and content, which leads to minimum DCN failure probability against a region failure. To make the scheme more scalable for large-scale networks, a heuristic is proposed by dividing the problem into two subproblems (i.e., DCN placement and content placement).
- Extensive numerical experiments are carried out based on the real gridded data of U.S. national seismic hazard map [22] to demonstrate our proposed network vulnerability assessment scheme and to validate the efficiency of the proposed ILP and heuristic for DCN and content placement under nonuniform spatial and intensity distribution of a potential disaster.

The rest of the paper is organized as follows. Section 2 introduces the scheme for network vulnerability evaluation. The ILP for optimal DCN and content placement and the corresponding heuristic are presented in Sections 3 and 4, respectively. We provide the numerical results in Section 5, and conclude this paper in Section 6.

2. Network vulnerability evaluation

We consider a network with deployment area Z and denote it as a graph $G = (V, E)$, where V is a set of nodes and E is a set of network links.

2.1. Probabilistic region failure model

A real-world disaster (or attack) is usually confined in a specific geographical region. A network component (like a link or node) in this disaster region will fail with certain probability, and such a failure probability depends on the intensity of failure, the distance to failure center and also the dimension of the component (such as the length of a link). To capture these key features of a region failure, we adopt the general probabilistic region failure (PRF) model proposed in [17].

- ***PRF model definition*:**

(1) As illustrated in Fig. 2, the PRF is defined by a set of consecutive concentric annuluses with radius $r_i, i = 1, \ldots, m$.