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Connectivity reliability and topological controllability of infrastructure networks: A comparative assessment

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ABSTRACT

As infrastructure systems evolve, their design, maintenance, and optimal performance require mature tools from system reliability theory, as well as principles to handle emerging system features, such as controllability. This paper conducts a comparative study of the connectivity reliability (CR) and topological controllability (TC) of infrastructure systems in terms of three aspects: topology, robustness, and node importance. Taking eight city-level power transmission networks and thousands of artificial networks as examples, this paper reveals that a dense and homogeneous network topology is better to satisfy CR and TC requirements, than more common sparse and heterogeneous networks when node attributes are generic. It is observed that the average degree's impact on CR is more significant than on TC, while degree heterogeneity is more significant on TC. When node attributes are accounted for, for generators the reliability-based node importance measure may underestimate some important nodes in terms of TC, and vice versa—an issue not observed for substation nodes. The findings in this paper suggest a potential new direction to enhance reliability-based design by integrating it with emerging controllability-based measures relevant in the future as infrastructure networks increase reliance on information systems.

1. Introduction

Networked infrastructure systems (e.g., water, power, telecommunication and transportation), are of critical importance to modern societies. Because of their networked nature, once one component is damaged by a natural, internal or deliberate hazard, other components may malfunction as well, which naturally requires studying their system-level reliability against disruptions [1]. The reliability of infrastructure system refers to the ability of the system to provide adequate services to its customers [2]. System reliability studies show that connectivity reliability (CR) is used as a necessary condition for more sophisticated function-based reliability. Together, these concepts have enabled infrastructure engineering research and implementation to mature and be used in practical reliability-based design [3–5], reliability-based maintenance and management [6], and reliability-based restoration and optimization [7,8] among others.

As infrastructure systems evolve and rely on information technologies more intensively, understanding their controllability [9] also becomes essential. In controllability theory, a system is controllable if it can be driven from any initial state to any desired final state within finite time with a suitable choice of inputs [9]. In this paper, we argue that traditional reliability approaches need to be complemented with controllability management principles to be able to design and manage future smart infrastructure systems. Systematic comparisons are necessary between reliability and controllability features of infrastructure systems so as to understand how the two approaches differ (both at the network level and the element level), or can be used complementarily.

Network CR analyses are typically performed by repeated computational simulations of network connectivity given samples of hazard realizations or failure sequences [10–12]; typical approaches rely on various Monte Carlo simulation strategies, including Markov Chain Monte Carlo [13], and Subset Simulation [14], among others [15]. Some advanced sampling methods are also applied, such as importance sampling [16] and Latin hypercube sampling (LHS) [17,18]. These simulation-based

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approaches allow for straightforward applications of deterministic network analysis algorithms to a wide class of lifeline network problems, including disconnections and functional requirements. However, the sampling nature of simulation-based approaches may require a large number of simulations to achieve an acceptable level of convergence in the results, especially for low-probability events and large scale systems [19].

As an alternative, researchers are also developing various non-simulation-based approaches, including the Disjoint Product Technique (DPT) [20], Binary-Decision Diagrams (BDD) [21] and their improved versions as Ordered Binary Decision Diagrams (OBDD) [22], the Dotson algorithm [23], Recursive Decomposition Algorithms (RDA) [24], Matrix-based System Reliability (MSR) methods [25], universal generating function methods [26], Combinatorial Recursive Methods [27], Linear programming approaches [28], sequential compounding methods (SCM) [29,30], and algorithmic enumeration [31] among others. In these methods analytical insight is sought and guaranteed approximations or bounds are also unraveled despite their high computational complexity.

Alternatively, fuzzy logic, uncertainty theory, and imprecise probability methods are also advancing. For instance, Feng et al. [32] presented an imprecise system reliability method based on survival signature, while He and Zhang [33] conducted a fuzzy reliability analysis using cellular automata for network systems, and Hosseini and Wadbro [34] employ uncertainty theory to dispense with the use of probability distributions or fuzzy membership functions. In recent years, scholars have also developed reliability models aiming to specific systems, such as multistage systems [35,36] and correlated failure systems [37,38] to name a few.

Among the mentioned methods, RDA is one of the most transparent in network reliability computation. At its core, RDA identifies the shortest path from a source element to a sink element in a network (or graph), and proceeds with a recursive decomposition by using the Boolean logic and associated probabilistic operations to quantify cut set likelihoods (i.e., joint failures of network components that cause disconnection) and link set probabilities (i.e., joint survivals of components that ensure connectivity). Liu and Li [39,40] proposed RDA efficiency improvements based on network reduction approaches. However, RDA still suffers from the curse of dimensionality for large-size networks, because the number of disjoint cut sets and link sets increases exponentially with network size. As an alternative, Lim and Song [19] and Lim et al. [41] proposed a Selective RDA (S-RDA), which identifies the most reliable paths, i.e. critical disjoint cut sets and link sets (and thus a set of bounds) that have dominant contributions to the likelihood of network connection or disconnection. The S-RDA thus searches a smaller state space and can obtain narrow bounds on the failure probability efficiently. Hence, this paper computes network CR via S-RDA, as described in Section 2.1.

The combinatorial nature of system reliability is also present in the emerging notion of topological controllability (TC) of complex networks, as it integrates classical control theory and network science, anticipating future smart networked systems. Lombardi and Hornquist [42] applied the linear system controllability principles to networks inspired by biology. A node is in this context controllable if an external signal can be applied which can adjust node properties in finite time to an arbitrary value, regardless of the levels of the other nodes. However, these ideas are not directly applicable to large scale networks because of computational complexity. Alternatively, Liu et al. [9] developed analytical tools to identify the set of driver nodes (by finding a maximum matching of a bipartite graph version of the original system) that can in principle guide or control the system's entire dynamics. Liu's algorithm identifies minimum driver node sets even for large scale networks. However, many configurations admit the minimum driver nodes set, among which some nodes are always the driver nodes. These nodes are called critical nodes. There are also some nodes that sometimes are driver nodes, and thus defined as intermittent nodes. The rest of the nodes are called redundant nodes. More recently, Jia et al. [43] developed an analytical framework to identify the category of each node, identifying two distinct control modes in complex networks: centralized versus distributed control.

As for the engineering applications of TC principles, though Diao and Rauch [44] have introduced TC theory into infrastructure systems, it is still necessary to explore how the TC of infrastructure networks relates to their CR which typically guides infrastructure design and upkeep. Also, the role of network topology on CR- and TC-based performance is unclear now. To design and manage infrastructure systems, identifying critical components is important, and whether CR-based approaches match or mismatch with TC-based approaches should be unraveled. Component importance is also key to understand how systems behave under random failures or target attacks [45].

Metrics to evaluate and quantify CR and TC constitute the core of the comparative study. Some TC-based metrics have been developed and applied in the network science community. For example, Yan et al. [46] developed a metric in terms of control cost, which captures the energy needed to control networks. The Control Robustness Index proposed by Wang et al. [47] is a metric to assess controllability against failure and attacks. The minimal number of driver nodes is widely used for quantifying the TC attributes of networks [9]. However, the cardinality of the minimal driver node set fails to compare controllability properties among different network scales. As an alternative, in this paper the authors develop a new way to quantify TC, named the Controllability Index (CI), which not only eliminates the impact from network scale, but also identifies the system TC attributes fairly.

As for the node importance measures in terms of TC, a few metrics are proposed. Among them, monitoring the frequency that a node participates in all minimal driver node sets or control backbone is common [48]. But this metric may result in importance ties for some of the nodes, because some nodes are always driver nodes (critical nodes) and some nodes are never driver nodes (redundant nodes). Another node importance metric is called Control Centrality [49], which quantifies the ability of a single node to control a directed weighted network, although it is not suitable for general unweighted networks. This paper proposes a metric for quantifying the node importance that relies on removing a node, and monitoring changes on CI and on the number of minimal control schemes. The proposed metric could capture a node's contribution to the system controllability, while minimizing importance tie levels even among unweighted networks.

With the proposed metrics, this study conducts a comparative investigation of infrastructure networks connectivity reliability (CR) and topological controllability (TC) features at both network and node levels. At the network level, this paper not only discusses how link density and degree heterogeneity affect both CR- and TC-based system performance, but also conducts a comparative analysis on CR- and TC- based system robustness characteristics. At the node level, this study discusses similarities and differences between CR- and TC-based node importance measures.

The rest of this paper is structured as follows: in Section 2, this paper provides an overview of S-RDA for CR assessment, and proposes a CR-based node importance (NI) measure. Section 3 presents TC theory and develops an NI measure in terms of TC indicators. Section 4 detects how link density and degree heterogeneity impact both CR and TC features. Section 5 provides a robustness analysis based on both CR and TC measurements. Node importance in terms of CR and TC is then quantified and compared