Knowledge Discovery of Network Topology and Its Applications: A Case Study of the Internet (Postprint)

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Abstract

This paper first elaborates on the definition of network topology structure, identifies the distinctions between analytical methods for discovering knowledge about network topology structure and those of traditional disciplines, and uses the Internet as a case study to review the main conclusions of Internet topology analysis and present examples of applying Internet topology knowledge. Finally, it illustrates the significance of acquiring new knowledge through network topology structure analysis from both practical and disciplinary development perspectives.

Full Text

Preamble

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Abstract

This paper first defines network topology and highlights the fundamental differences between analytical methods for discovering network topology knowledge and those employed in traditional disciplines. Using the Internet as a case study, it reviews the principal findings of Internet topology analysis, provides concrete examples of applying Internet topology knowledge, and finally elucidates the significance of acquiring new knowledge through network topology analysis from both practical utility and disciplinary development perspectives.

Keywords: network structure, Internet topology, topology analysis, network science

1 Introduction

Networks of various kinds exist extensively in nature and human society, including infrastructure networks such as railway, highway, and aviation transportation systems, power grids, as well as technological networks like the World Wide Web (WWW), peer-to-peer (P2P) networks, and the Internet that have become widely deployed in recent years. A typical network consists of numerous nodes and edges connecting them. Generally, nodes represent individuals or organizations in the real world, while edges represent relationships between them. For instance, in the Internet, autonomous systems (ASes) can be represented as nodes, with edges representing connections between them, forming an AS-level network topology. Alternatively, if routers in the Internet are treated as nodes and connections between routers as edges, this yields a router-level Internet topology.

When mathematicians and physicists study networks, they typically abstract away physical details to capture essential properties. This abstraction manifests as disregarding specific physical locations or sizes of nodes, as well as the length, curvature, or intersections of edges, focusing solely on whether nodes are connected. For example, when Euler solved the Königsberg seven bridges problem in 1736—an era when geometry focusing on length and size dominated mathematical thought and few studied configurations independent of metric properties—he abstracted two islands and both riverbanks into four points and the seven bridges into connections between these points, thereby pioneering topological research. When a network is abstracted in this manner, independent of node positions, sizes, and edge geometries, the resulting properties are called topological properties, and the corresponding structure is termed network topology.

Network structure and function constitute the core of network theory research. Network structure is typically characterized by statistical features such as degree distribution, clustering coefficient, average shortest path length, and degree-degree correlation, while network function is reflected through dynamic processes on the network. These two aspects are not independent but possess an essential, inherent relationship: structure generally determines function, and function in turn influences the evolution of network structure. For example, different structures in transportation networks lead to significantly different network capacities, while increased traffic may prompt the addition of new routes, thereby affecting network evolution.

2 Relationship Between Large-Scale Complex Network Topology Analysis and Other Disciplines

Knowledge of network topology must be acquired through topology analysis. The primary objects of interest in current network science are large-scale complex networks such as the Internet, with network topology analysis methods forming the core content of the discipline. From a disciplinary perspective, this research builds upon foundations including traditional statistics and graph theory. Due to the massive scale, diversity, dynamics, and complexity of complex networks, statistical processing is essential. Graph theory provides concise and precise methods for describing networks, becoming a common language and necessary tool for researchers.

However, network topology analysis methods differ substantially from traditional disciplinary approaches. Conventional statistics focuses on analyzing attribute data, whereas network structure analysis typically emphasizes relational data. Attribute data refers to data owned by individual nodes or groups of nodes themselves, while relational data concerns relationships between nodes, between communities, and at the global or block levels—data jointly possessed by two or more nodes. Relational and attribute data represent different analytical objects, and their analytical methods differ considerably.

Classical graph theory typically studies objects with only a few or several dozen nodes, allowing mathematicians to perform precise network optimization. In contrast, complex network structure analysis often deals with thousands, millions, or even billions of nodes, necessitating abstraction at different scales. Excessive abstraction may lead to conclusions that diverge significantly from reality, sparking various debates and requiring researchers to examine problems from multiple scales appropriate to actual conditions. Conclusions discovered at one scale may not hold at another. For example, the degree distribution of the Internet' s AS-level topology follows a power law [1,2], whereas at the router-level topology, due to limitations on router interface counts, the degree distribution clearly does not follow a power law. Differences in scale perspectives among researchers from different disciplines have recently sparked intense debates, exemplified by computer networking researchers questioning conclusions from network science [3]. This is analogous to comparing the work of Cook Ding from the fable "Pao Ding Jie Niu" with that of an ordinary chef: Cook Ding, through repeated practice, mastered the structure of an ox (i.e., the underlying patterns—what we now call a "scientific problem") to guide his practice (dissecting the ox), while an ordinary chef need not perform Cook Ding' s work, simply turning beef into steaks and dishes to directly satisfy customers—a more "technical problem." In other words, these represent two distinct levels of work, both valuable.

Network structure analysis has played important roles in research and practice across social networks, technological networks, and biological networks, with the Internet serving as a typical example. As a real-world network, the Internet has evolved from its initial four nodes into today' s global information infrastructure. Its deep application development and ubiquitous presence have profoundly transformed how people work, live, and learn, making it a truly massive system with complex structure. The scientific significance and application value of Internet topology research are receiving widespread attention from academia, industry, and military sectors. The following sections provide detailed explanations of Internet topology analysis results and their applications.

3 Internet Topology Characteristics

Despite their diversity, networks can all be described using graphs. Adjacency matrices and adjacency lists contain complete network information and represent traditional graph representation methods, but neither provides intuitive insight into a given network' s characteristics. Due to the typically large scale and complex structure of networks, concepts, statistical features, and metrics are needed to intuitively characterize a network' s principal structural properties. Commonly used metrics include node degree distribution, average path length, clustering coefficient, degree-degree correlation coefficient, betweenness, and core number. Recent analysis of Internet topology has revealed numerous characteristics:

(1) Power-Law Discovery

In Internet topology research, Faloutsos et al. analyzed three BGP routing data sets from the National Lab for Applied Network Research (NLANR) between 1997-1998 and one traceroute dataset from 1995, discovering four power laws in Internet topology. Their findings were published in SIGCOMM' 99 and *Computer Communication Review* [1]. This empirical conclusion refers to an approximate power law. Most importantly, this finding fundamentally reveals differences between nodes, showing that—unlike previously dominant random network models [4]—the AS-level topology contains a few high-degree nodes and many low-degree nodes. This discovery attracted widespread attention and sparked a research boom. It must be emphasized that a power-law degree distribution at the AS level does not imply power-law behavior at other scales (e.g., router-level topology).

In fact, various subnets comprising the Internet's underlying infrastructure often exhibit star or tree structures that do not follow power laws. However, when these subnets interconnect, power-law characteristics emerge at the macroscopic AS level—a phenomenon of "emergence."This resembles how interactions between individuals produce economic institutions in social sciences or how interactions between neurons produce intelligence.

(2) Small-World Networks

Reference [5] provides experimental data demonstrating that the Internet AS-level topology exhibits short average distances and relatively large average clustering coefficients, constituting a "small-world" network. Reference [6] examines network evolution from 2001-2006, showing that while the number of nodes and edges in the Internet AS topology doubled, the average distance remained between 3.62–3.82 and the average clustering coefficient between 0.242–0.296, further confirming the small-world characteristics of the Internet AS-level topology.

(3) Assortativity and Disassortativity

M.E.J. Newman examined degree-degree correlations across multiple networks [7,8], finding that the Internet AS-level topology exhibits disassortativity—high-degree nodes tend to connect with low-degree nodes. Reference [9] investigated hierarchical correlations from a k-shell decomposition perspective, discovering hierarchical disassortativity in the AS-level topology (outer layers tend to connect with inner layers), while the router-level topology shows hierarchical assortativity. In contrast, both AS-level and router-level topologies exhibit degree-degree disassortativity.

(4) Rich-Club Structure Among High-Degree Nodes

Reference [10] observed that in the Internet AS-level topology, a small number of nodes with many edges tend to interconnect preferentially, metaphorically termed the "rich-club phenomenon." This can be quantified using the rich-club connectivity coefficient (r/N), which represents the ratio of actual edges L among the top r highest-degree nodes to the maximum possible edges among them. If (r/N) = 1, the top r nodes form a fully connected subgraph.

The authors compared the rich-club coefficient of the Internet AS topology with common network models, finding that an extremely small proportion of high-degree nodes have numerous connections, with a rich-club coefficient exceeding those of common models. They also partitioned all nodes into 20 equal segments by degree and compared inter-segment connection patterns, concluding that high-degree nodes exhibit dense interconnections. However, reference [11] disputed this phenomenon, arguing that a simple rich-club coefficient is misleading for distinguishing the rich-club phenomenon and should instead be based on random networks with identical degree sequences. They proposed a method defining the ratio of a network' s rich-club coefficient to the average coefficient of random networks with the same degree sequence; values greater than 1 indicate a rich-club phenomenon.

Reference [12] offered another statistical approach: calculate the relative rich-club coefficient n times, then compute the probability that this coefficient is less than or equal to 1. If this probability is less than (set at 5% in the paper), the network exhibits a rich-club phenomenon. However, the authors provided a counterexample showing this method also fails in certain cases. Thus, while detection methods for the rich-club phenomenon continue to evolve, they remain imperfect. Researchers from different fields provide definitions reflecting their disciplinary characteristics, revealing different mindsets between engineering and physics researchers.

(5) Symbiotic Effect

Through analysis of multiple real networks, reference [13] discovered that in the Internet AS-level topology, the rich-club structure appears consistently based on two different centrality measures (degree and betweenness), with both rich-club coefficients converging—a phenomenon termed the “symbiotic effect” of rich-club structures. Empirical evidence shows many real networks, including Internet router-level topology, protein interaction networks, and scientist collaboration networks, lack this effect, whereas widely used BA models [14] and their variants ESF [15], GLP [16], and PFP [17] all exhibit it. This effect can serve as a criterion for network modeling, helping select whether to adopt BA models and their variants by distinguishing macroscopic network structures.

(6) Self-Similar Structure

Research on China’s Internet topology reveals that despite unique considerations in network construction and planning—such as different social systems, operator characteristics, and large user populations—China’ s Internet AS-level topology shares the same principal macroscopic features as the global Internet AS-level topology and can be simulated using the same PFP model [2]. This demonstrates self-similarity between China’ s Internet topology as a local part and the global Internet topology as a whole. Traditional self-similar structures are characterized through fractal concepts [18]. Reference [19] proposed a conceptual Medusa model for Internet structure: approximately 70% of nodes form a giant connected component that can remain connected without passing through the nucleus. This subgraph exhibits self-similar structure characterizable by fractal methods.

(7) Local Clustering Phenomenon

Reference [20] investigated local clustering characteristics in the Internet AS-level topology through three aspects: correlation between local clustering coefficient and node degree, triangle distribution, and redundancy of connected subgraphs. Despite the seemingly free choice of connections between autonomous systems, strong local clustering exists under regional and national constraints. This indicates Internet connections are not randomly established; nodes tend to connect with geographically local nodes. Additionally, redundancy exists among connections between low-degree nodes, enriching routing options and enhancing network robustness. Local clustering properties significantly impact network performance. Based on observed local clustering phenomena [20], reference [21] improved the PFP model and proposed the LDPFP model.

(8) Centric Structure

Reference [9] defines as “centric structure”the tendency of nodes at various layers after k-core decomposition to connect with nodes in the deepest core (nucleus). The Internet AS-level topology exhibits obvious centric structure, which can reduce network average distance and improve routing efficiency.

(9) Hierarchical Structure

The hierarchical structure of the Internet AS-level topology has multiple characterizations: the Jellyfish model [22] visually represents the AS-level topology as a jellyfish shape based on node degree; the Medusa model [19] divides the topology into three parts based on core number—the deepest core composed of all maximum core-number nodes, a giant connected component in the remaining portion, and other isolated components; reference [6] proposed a core-periphery model highlighting different evolution patterns for core and peripheral regions; and reference [9] introduced hierarchical correlation and centric structure, all reflecting the Internet' s hierarchical nature from different perspectives.

(10) Robust Yet Fragile

Internet topology exhibits dual "robust yet fragile" characteristics with different formation mechanisms at different scales. At the AS level, it simultaneously demonstrates [43]: robustness against random node failures and extreme vulnerability to targeted attacks—removing just a few critical nodes can cause network-wide collapse, known as the Achilles' heel. This vulnerability stems from degree distribution heterogeneity.

At the router level, the Internet effectively tolerates uncertainties considered during design (demonstrating robustness) but becomes extremely vulnerable to unconsidered uncertainties (such as IP prefix hijacking or distributed denial-of-service attacks) [44]. This dual characteristic arises from whether factors are considered during network design and optimization, with its root cause not being degree distribution.

4 Applications of Internet Structural Knowledge

Network structural knowledge undoubtedly has broad utility. It can address issues related to network performance, survivability, secure transmission, and energy efficiency. For example, reference [23] uses node degree as a factor in OSPF routing protocol link weights to diversify paths and balance traffic; reference [24] detects IP prefix hijacking using macroscopic dynamic changes in edge cutsets of the AS topology; references [25-26] apply structural knowledge to scalable routing. In recent years, the authors and colleagues have explored applications of Internet topology knowledge in traffic optimization, survivable routing, server deployment, and routing algorithm design, with some gradually being implemented in practical systems. Specific examples include:

(1) Traffic Optimization: Using Internet topology knowledge to reduce backbone network traffic and optimize performance, we proposed PPM (P2P Matcher) technology to align upper-layer P2P networks with underlying network topology [27-30]. The main idea optimizes neighbor selection and data scheduling in P2P applications based on node IP prefixes and AS numbers to increase P2P traffic locality. This work preceded the internationally similar P4P concept [31] by three years. In 2009, we also proposed a network coding-based data scheduling algorithm combined with location awareness to optimize P2P application traffic [32]. Compared with previous best methods, this approach can reduce BitTorrent-like service traffic by half, approaching theoretical limits and achieving a win-win-win situation for ISPs, P2P content providers, and end users. Parts of this work are becoming central to national communication industry standards [29], with all domestic network operators and major equipment manufacturers participating in the standardization process. Additionally, addressing the widespread presence of NAT in the Internet, we developed solutions for P2P traffic optimization across private networks [33-34] to fully utilize access network resources, further increase P2P traffic locality, and reduce inter-domain and backbone network traffic.

(2) Network Survivability: To construct more diverse network paths in overlay networks with shorter average backup path lengths and higher forwarding efficiency, we utilized betweenness and core numbers to characterize network features and proposed an efficient algorithm for selecting forwarding nodes in overlay networks [35]. Additionally, by leveraging characteristics of core numbers and degrees combined with forwarding node location information and link performance measurements, we generated more reliable and practical backup paths [36], providing technical support for implementing survivable routing.

(3) Server Deployment: Reference [37] investigated the inefficient deployment of overlay relay servers from a network structure perspective. Utilizing the Internet' s disassortative characteristics and rich-club structure (where high-degree nodes tend to connect with low-degree nodes while also densely interconnecting with other high-degree nodes), we proposed a heuristic scheme called DROP (Degree Rank based Overlay relays Placement). This scheme effectively selects locations for overlay relay nodes using minimal physical topology information to optimize redundancy and communication reliability across the entire Chinese Internet.

(4) Routing Algorithm Design: Reference [38] designed a distributed heuristic routing selection algorithm called BFSQ to maximize multipath overlay routing efficiency by leveraging the relatively stable and moderately sized AS-level topology information. Simulation results show BFSQ can effectively select multiple overlay paths for end nodes and can be deployed in practical overlay systems.

(5) Scalable Routing: Reference [39] proposed designing scalable routing algorithms using scale-free and strong clustering characteristics, treating the network as a backbone tree plus many shortcuts. Since scale-free networks have few long shortcuts, spanning trees constructed using the backbone tree and a small number of long shortcuts can achieve low bounds on routing table size and stretch factor, with experiments validating the approach. Reference [40] proposed a series of maximum-degree landmark-based compact routing algorithms—HDLR, HDLR+, and NIHDLR+—demonstrating superior performance over generic compact routing algorithms, with simulations confirming their effectiveness.

(6) Capacity Enhancement: Using network structural knowledge to expand network capacity, we proposed edge-deletion-based capacity expansion methods

[41] and optimal node capability allocation based on node degree under fixed total node capability [42] for networks dominated by shortest-path routing.

(7) Energy Efficiency: Reference [45] achieves energy savings by designing energy-aware network topologies using aggregation and sleep methods, making the number of active devices positively correlate with network load so more devices sleep when load decreases. Additionally, through P2P traffic optimization, server deployment methods that significantly reduce traffic volume, and private network traversal solutions [33-34] with added proxy awareness, energy efficiency is improved.

(8) Economic Analysis: Reference [46] integrates topology research with institutional economics research, converging on network architecture to analyze derived contracts. It focuses on end-user network opening technologies to increase autonomy, enrich contractual relationships, and promote network economic development. This research helps understand the microeconomic significance of Internet architecture and its systems while proposing economic-level evaluation methods for network architecture practicality.

5 Summary and Outlook

Just as understanding structure is fundamental to human cognition and transformation of objects, mastering network structure is essential for understanding and improving networks. Internet topology represents the most basic intrinsic attribute of Internet information infrastructure. The discovery of Internet topology characteristics and knowledge and their applications are rapidly developing. Current hot topics in information systems engineering—such as cloud computing, triple-network convergence, smart planet, social computing, and the Internet of Things—all depend on the Internet as information infrastructure. Revealing Internet structure and deeply understanding its knowledge can provide scientific foundations for effective network utilization and rational construction of Internet-based information systems engineering, offering theoretical guidance for network construction, upgrades, upper-layer application optimization, and design of next-generation network architectures and protocols.

The Internet serves as a typical network instance in network science. In-depth research and application of its topology knowledge can enrich network science and promote development of this emerging discipline. Network science is broadly interdisciplinary and complex, involving mathematics, physics, computer science, systems science, and other fields. Within mathematics, it frequently involves graph theory, statistics, stochastic processes, and topology. Network science' s general descriptions of complex systems and summarized patterns also provide new perspectives and guidance for in-depth study of Internet topology and other specific networks.

We anticipate that in the near future, more simple and elegant scientific discoveries in network structure analysis will provide methodological guidance for technological progress, leading to concise and efficient technical methods that serve society.

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Note: Figure translations are in progress. See original paper for figures.