22. Modeling the Network Topology

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22.1 Introduction

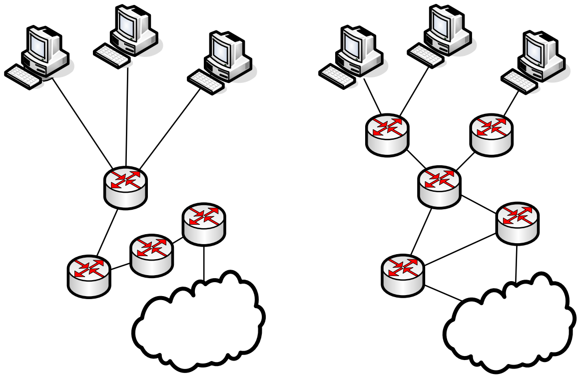
Network topologies are one major building block for data communication. They describe how network entities are directly interconnected with each other and thus define how information *may* flow. Such a structure of node relations can be built on different layers resulting in a physical or logical topology. The first will be constructed while connecting devices by a physical medium. On top of this structure, data exchange can be arranged via the network and application layer creating a logical or overlay topology.

Network communication depends on its underlying structure. This drives protocol performance, and has impact on routing behavior and complexity. Choosing an appropriate topology for simulations, analytical studies, or experiments is an important task. As a simple example consider Figure 22.1(a) and 22.1(b). Both scenarios represent a local area network that connects end devices via routers to the Internet, but differ in topological properties. Protocol evaluation thus may lead to completely different results. For instance, failover mechanisms of a routing protocol cannot be observed for a setting shown in Figure 22.1(a), as redundant paths are not available to bridge broken connections.

The network topology and its properties are important ingredients for protocol and system evaluation. They should be chosen characteristic of the problem under observation. Thus, the first step in selecting an appropriate topology is to clarify the scenario, in which the protocol will operate. In many cases, though, the characteristic properties of the underlying network are unknown or only vaguely specified. For this reason, there is a tendency to enrich topology modeling by network measurement. However, working with real data especially for large, evolving networks such as the Internet cause specific problems. First, it is an intricate task to retrieve real data for such structures. Second, every measurement represents only a snapshot, which may quickly obsolete. Moreover, sets of realistically large sizes may be difficult to process with currently available memory and CPU cycles. Thus, instead of applying the problem to a dedicated network topology, the corresponding topology space should be explored.

In this chapter, we will introduce some common topology models. The remainder is structured as follows: We present the basic abstraction principle for network topologies in Section 22.2, and explain how network models can

Reference information:
Matthias Wählisch,Modeling the Network Topology, In: Modeling and Tools for Network Simulation,
(Klaus Wehrle, Mesut Günes, James Gross Ed.), pp. 471--486, Heidelberg: Springer, 2010.



(a) Non-redundant network

(b) Redundant network

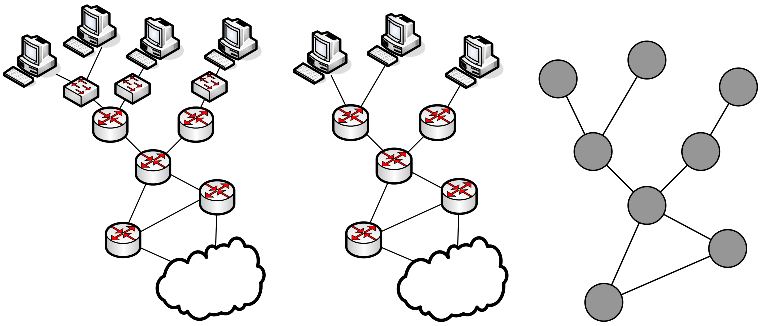
Fig. 22.1: Different network topologies

be characterized in Section 22.3. Section 22.4 describes basic topology models. Finally, we discuss approaches to model the Internet in Section 22.5.

22.2 Abstraction of Network Topologies by Graphs

Physical and logical topologies consist of entities which are in a relationship with each other. In most networks, these entities represent different types. The topology of a computer network, for example, includes end hosts linked to switches (layer 2) connected via routers (layer 3), cf. Figure 22.2(a). In this chapter, we address the modeling of the resulting structures, i.e., the network.

The modeling process includes several levels of abstraction. A network topology model forms the structural properties of the network. Dedicated instances of network devices such as different types of routers, switches, or end system nodes are neglected based on unification (cf. Figure 22.2(a)). The second step 'eliminates' all entities that are transparent to the layer under observation and subsumes devices. In our example, we focus on the local routing structure. Thus, switches will be omitted and end devices can be merged to a domain represented by a single entity (cf. Figure 22.2(b)). At this stage, our network includes routers, end user domains and an inter-network connection. From a structural point of view, the inter-network connection as illustrated does not include any further information. The last step transforms



(a) Redundant network (b) Redundant network (c) Graph representation

Fig. 22.2: Abstraction process of network topologies

the concrete network in an abstract graph representation (cf. Figure 22.2(c)). Nodes and links equal *edges* and *vertices*, respectively.[1]

A graph G is a set of vertices connected via edges. The set of vertices is usually denoted by V, and the set of edges by E. Edges may be directed or undirected, and hence allow to model uni- and bidirectional, as well as symmetric and asymmetric links. Figure 22.2(c) shows an undirected graph. Vertices and edges can be extended by attributes, e.g., weighted edges, which represent link costs. Each vertex possesses an inherent structural property: its *degree*, usually denoted by k. The degree of a node is the number of its connections (which equal its number of nearest neighbors). In the case of directed edges, the degree can be split in in- and out-degree.

The degree property enables the indirect modeling of different node types. Considering the example in Figure 22.2, an end user domain has been merged to a single vertex. The inner structure of such domains is not under consideration, and they are connected to a single router. Consequently, the domains can be identified by vertices with a degree of 1. This simplification does not allow the modeling of multi-homed or redundant sites.

Typically, the characterization of a dedicated vertex is not very helpful and does not reflect the whole graph (or network). In the following, we describe properties of the complete graph.

22.3 Characterizing Graphs

The graph model can be based on two approaches: ad-hoc and measurement-based. An ad-hoc model is developed independently of real measurements. In

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[1] In the following, we will use both, the network engineering and graph term, interchangeably.

contrast to this, a measurement-based model tries to reconstruct graph properties or to reproduce the reasons for it. Ad-hoc as well as measurement-based approaches require a characterization of graphs to verify the approximation of the real network.

In this section, we summarize some basic properties of graphs. Based on graph metrics, we can describe and compare networks. Each type of network exhibits a different structure. A mesh network, for example, includes significantly more inter-connections than a local area network. This property should be preserved in the corresponding topology model. However, usually a network cannot be described by a single (simple) metric, but metrics may be correlated. The latter may be used to restrict the set of properties.

Metrics have a global or local meaning for the graph.

The basic property of a graph is the number of edges $|E|$ and vertices $|V|$. For an undirected graph, it follows the average node degree $\langle k \rangle$ by $\langle k \rangle = 2|E|/|V|$. More significant (and often used) is the degree distribution $P(k)$, which calculates the probability that a randomly selected node has degree k. We denote the number of nodes with degree k by $n(k)$, then:

$$P(k) = \frac{n(k)}{|V|} \tag{22.1}$$

It is worth noting that based on this probability distribution the average value $\langle k \rangle$ can be evaluated. In this case, $\langle k \rangle = \sum_{k=0}^{k_{max}} k \cdot P(k)$.

Equation 22.1 calculates the degree distribution for a general instance of a network. Several realizations of networks may belong to the same (statistical) class of graphs that admit equal distributions. There are three common degree distributions [122]:[2]

Poisson distribution

$$P(k) = e^{-\langle k \rangle} \cdot \frac{\langle k \rangle^k}{k!}$$

Exponential distribution

$$P(k) \propto e^{-k/\langle k \rangle}$$

Power-law distribution

$$P(k) \propto k^{-\gamma}, k \neq 0, \gamma > 0$$

A closer insight into the interconnection properties of the graphs is given by the joint degree distribution . This correlation law defines the probability that a randomly selected edge connects nodes with degree k_1 and k_2. Let $m(k_1, k_2)$ denote the number of edges out of the total $|E|$ edges that connect two nodes of degrees k_1 and k_2 in an undirected graph. Then the correctly normalized joint degree distribution is calculated as

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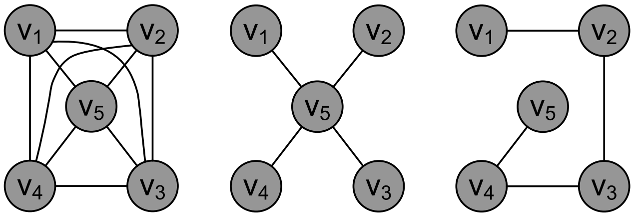
[2] The symbol $\propto$ means “proportional to”.



(a) Full Mesh (b) Star (c) Chain

Fig. 22.3: Three extreme graph topologies

$$P(k_1, k_2) = \frac{m(k_1, k_2)}{2|E|}$$

It does not only describe the one hop neighborhood structure of an average k-degree node, but can also be used to derive other well-known measures [333], [303]. Note that the single node degree distribution $P(k)$ does not directly follow from integration, but requires a bias correction factor, i.e., $P(k) \propto \sum_j P(k,j)/k$.

Delay sensitive applications or routing protocols are affected by the number of intermediate nodes between the source and destination. They adjust buffers or decide on a forwarding path based on the distance between nodes. The distance between two nodes is the length of the *shortest path* between them. In graph theory, this class of paths is also called geodesic . The distance distribution $d(x)$ measures the probability that two randomly selected nodes are connected via distance x, which typically is calculated in hops. The length of the longest shortest path taken over all pairs of nodes is called diameter of a graph, but in general the metric is not well-defined. In some publications, the diameter describes the average shortest path length [122], as well.

The average shortest path length $\langle d \rangle$ for an undirected graph is quantified as follows: Let $d(i,j)$ denote the distance of a shortest path between the two nodes i and j, then the normalized average path length is given by:

$$\langle d \rangle = \frac{2}{|V|(|V|-1)} \cdot \sum_{i \neq j} d(i,j)$$

In any forwarding scenario, intermediate nodes between source and receiver attain a distinct role. The number of shortest paths passing through a node m (or link) is quantified by the metric betweenness $B(m)$. To calculate the relative amount, we count all shortest paths between any two nodes passing m, and divide this by the number of shortest paths of all node pairs excluding m. Thus, if the total number of shortest paths between two nodes i and j is $B(i,j)$, and the number of these paths going through m is $B(i,m,j)$, than the betweenness of m is defined as follows [122], [159]:

Figure	$\langle k\rangle$	$\langle d\rangle$	$B(v_1)$	$B(v_2)$	$B(v_3)$	$B(v_4)$	$B(v_5)$
Full Mesh 22.3(a)	4	1	0	0	0	0	0
Star 22.3(b)	8/5	8/5	0	0	0	0	6
Chain 22.3(c)	8/5	2	0	3	4	3	0

Table 22.1: Structural properties of the graphs shown in Figure 22.3

$$B(m) = \sum_{i\neq m\neq j, i\neq j} \frac{B(i,m,j)}{B(i,j)}$$

Betweenness is a common metric in the context of traffic engineering, or social networks. This measurement quantifies the importance of a node in information exchange, and the load on such intermediate vertex. Assuming uniformly distributed traffic that follows shortest paths, the traffic passing through a node coincides with its betweenness. For comparison of different sized, directed networks, the betweenness of nodes and edges can be normalized by $(|V|-1)(|V|-2)$ and $(|V|(|V|-1))$, respectively [159].[3] Note that undirected graphs require an additional dividing factor of 2. The calculation of the betweenness in unweighted and weighted networks requires $O(|V||E|)$ and $O(|V||E| + |V|^2 \log(|V|)$ time, respectively, consuming $O(|V| + |E|)$ of memory [80].

Networks agreeing on one property may still differ in others. Table 22.1 presents the average node degree, the mean path length, and the betweenness for nodes of the graphs shown in Figure 22.3. For example, a star and a chain topology with the same number of nodes exhibit the same average node degree. Nevertheless, both topologies differ significantly in their robustness against attacks (average distance), and in their characteristic traffic flow per node (betweenness). In the case of a full mesh, the betweenness reveals that no vertex attains a dedicated role in the forwarding process. On the other hand, the central entity in the star topology can be identified easily.

22.4 Common Topology Models

In this section, we want to address the question of how to construct a graph that satisfy specific properties.

22.4.1 Random Graphs

The basic random graph model, and the corresponding theory have been derived by Erdős and Rényi [134, 135]. A random graph, which is also

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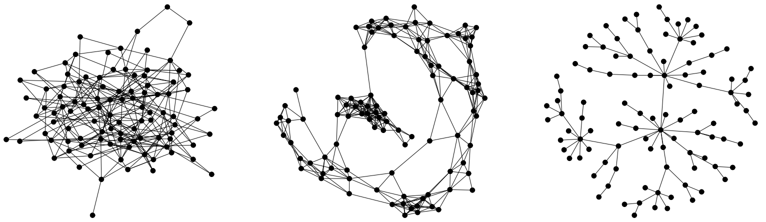
[3] The maximum value of betweenness is $|V|(|V|-1)$. For simplification, some authors use this for normalization of node and link betweenness [303].



(a) Random graph (b) Geometric random graph (c) Barabási-Albert graph

Fig. 22.4: Visualization of differently generated topologies

called Erdős-Rényi-graph, will be constructed as follows: Given a fixed number of nodes and a probability p, then each edge between two vertices will be constructed independently with probability p. The pseudocode is presented in RANDOM GRAPH ALGORITHM:

```
RANDOM GRAPH ALGORITHM $n, p$
    ▷ $A$ denotes the adjacency matrix of $G$ with $n$ vertices
    ▷ $p$ denotes the probability that two arbitrary vertices are connected
    ▷ getRandom() returns uniformly distributed a number over $[0, 1]$
for all $0 \leq i, j \leq n-1$
        do $A_{i,j} \leftarrow 0$
for all $0 \leq i, j \leq n-1$
        do if $p \leq$ getRandom()
                then $A_{i,j} \leftarrow 1$
return $A$
```

Another variant of the Erdős-Rényi-graph considers a fixed number of edges: Given the set of all graphs that have n vertices and m edges, one is uniformly selected. Both models generate a class of graphs with equal statistical degree properties. For large n, the random graph exhibits a Poisson degree distribution. All connections are distributed with equal probability over node pairs. Consequently, the classical random graph does not model clustering properties, which makes it almost unsuitable for implementing realistic networks. However, there are contributions on generalizing the random graph to correct these issues [334]. Detailed mathematical background in the theory of random graphs is presented in [67].

It is worth noting that the following construction procedure does *not* reflect the random graph model: Consider all graphs of a fixed number of vertices. They differ in numbers and combinations of edges, and attain topologies of differing degree properties. Choosing random elements from this set of graphs, will not lead to an unbiased sample of random graph. For example, the graph with no edges, or the full mesh topology represent a single instance. The selection process is thus inherently biased preferring graphs with the maximal number of link combinations.

22.4.2 Geometric Random Graphs – The Waxman Model

Physical connections between nodes of a computer network are not created arbitrarily but may follow cost aspects of cable lengths. An enhancement of the Erdős-Rényi-model are geometric random graphs. They account for the distance between two nodes and thus introduce preference aspects. The most well-established model for this class of graphs is the so called *Waxman graph*, which has been introduced to compare Steiner tree algorithms [489]. In this model, vertices are placed randomly on a Cartesian coordinate grid; the probability P that an edge connects two nodes u, v depends on their Euclidean distance $d(u,v)$:

$$P(u,v) = \beta \cdot e^{-d(u,v)/L\alpha},\ 0 < \alpha, \beta \leq 1$$

L denotes the maximal distance of two vertices. An increasing β increases the edge density. A decreasing α reduces the ratio of long to short edges. Based on these parameters, we can also adjust the average node degree. The Waxman graph is an appropriate model for small networks that include locality aspects.

22.4.3 Hierarchical Topologies

Larger computer networks typically consist of several levels. Hierarchical models decompose the network into tiers, e.g., transit domains connect stub domains that connect local area networks (LANs) [86]. The general idea is that each tier is represented by multiple graphs with identical properties. For this purpose a $2d$–grid is divided into separate sub-regions with a scaling dependent on the network type. This approach allows for inherent support by Waxman graphs. LANs are modeled as star. Sub-regions are connected step by step following a top–down creation process. The properties of constructing a network rely on the (sub–)graph models in use.

There are two common, basic hierarchical models in the context of computer networks: The *Transit–Stub* [511] and *Tiers* [120] model. The transit–stub graph supports two tiers, and node labels contain hierarchical information. Edges are associated with policy weights. In contrast, the Tier model supports a three level hierarchy. All nodes in a single domain are connected by a minimum spanning tree algorithm. Inter-domain connections are based on the Waxman model.

22.4.4 Preferential Linking – The Barabási-Albert Model

A preferential linking model implements the key concept that highly connected vertices are likely to become even more connected. The first model combining network evolution and preferential linking is the Barabási-Albert model [49]. Motivated by their analysis of the web link structure, Barabási and Albert observed that complex networks evolve continuously by the emergence of additional vertices, and that new vertices prefer the establishment of links with already well-connected vertices. Let k_i denote the degree of node i, then the probability P that a new vertex attaches to i is:

$$P(k_i) = \frac{k_i}{\sum_j k_j}$$

The basic construction algorithm works as follows: Starting with m_0 connected vertices, and a predefined fixed degree k, at each time step a new k–degree vertex l is added and linked with probability $P(k_l)$ to j randomly selected, already existing different vertices. An extended version including a rewiring option has been presented in [30].

All new nodes follow the same weight in preferential attachment. To dynamically adjust the weight of the preference, the Generalized Linear Preference Model (GLP) has been introduced with a weighting parameter β [82]:

$$P(k_i) = \frac{k_i - \beta}{\sum_j (k_j - \beta)}, \text{ with } \beta \in (-\infty, 1)$$

This model addresses representative path length and clustering. Both, the Barabási-Albert model and the GLP model exhibit a power law degree distribution.

22.4.5 Intermediate Results

Based on the models presented so far, we can create random topologies without clustering, networks that reflect preferences in locality or popularity, and hierarchical structures. Hierarchical models typically inherit properties from sub-models. The random graph, the Waxman model, and Transit-Stub as well as Tiers model can be summarized as ad-hoc models, which are typically inappropriate for large-scale, evolving networks. The Barabási-Albert model is an example for measurement-driven approaches trying to reproduce empirically observed properties of real-world structures.

Figure 22.4 visualizes the (geometric) random graph as well as the Barabási-Albert model. This illustration tries to give some intuition behind these models. However, it is worth noting that the same instance of a graph may be drawn differently resulting in quite different pictures. A graph should not be identified based on its visual structure but on its measurable properties.

22.5 Modeling the Internet

In this section, we focus on the modeling of the Internet topology. The Internet is a multi-tier network, which involves communicating components of the applications down to the network, and even the physical layer. Referring to the Internet topology means looking at the structure that is responsible for packet forwarding. We thus exclude structures such as the World Wide Web graph [359, 150].

22.5.1 Background

The term Internet topology is not well-defined. The Internet consists of edge domains (or access networks) connected to at least one router, which may serve several IP networks. Such an access router is typically part of a larger domain, consolidating multiple IP prefixes. Routers administrated by a single authority are aggregated within an *Autonomous System* (AS). Border routers of ASes peer with each other. Routing within ASes may follow different protocols, routing between ASes is based on a single protocol, currently BGP [386]. In contrast to *intra-domain routing* , *inter-domain routing* need not follow shortest path selection, but economical or political rules, for example. Peering between ASes may be private, or publicly located at Internet Exchange Points (IXPs). An AS of an Internet Service Provider (*ISP*) that agrees to accept and forward traffic to other ISPs, but does not run own access networks, is called a transit domain.

Modeling the Internet topology implies the choice of granularity, i.e., the type of resolved entities (the AS-level, router-level or IP-level), or a combination. Augmenting an AS structure with access networks (router-level networks) is not trivial as autonomous systems are not homogeneous and the inner structures may differ. Autonomous systems can be classified by administrative categories or peering relationships (cf. [119] and related work therein).

22.5.2 Topology Inference & Data Sources

The accurate modeling and analysis of the Internet topology require the observation of its current state. Gathering the complete Internet structure is a complex challenge, which cannot be entirely successful as there is no global view on all connections, nor do we have a method to validate routes and guarantee global consistency. Nevertheless, several measurement studies have been pursued over the last decade to understand the Internet structure and to provide researchers with a realistic Internet topology. For a detailed overview about Internet topology inference and its problems, we refer to the surveys [192], [121].

Topology inference is done on different levels of the Internet. IP paths may be discovered by traceroute. Using *alias resolution* mechanisms [121], IP interface addresses can be summarized and mapped to a single router. Both steps, however, are not trivial: ISPs filter ICMP messages used by traceroute causing incomplete data sets. Additionally, VPNs, tunnels, or MPLS paths cannot be revealed by such technique. The aggregation of different IP hops to a single router usually follows heuristic approaches. Further on, routing paths need not be symmetric, and source routing is almost everywhere prohibited. This complicates traceroute measurement and require several vantage points to explore the diversity of the routing layer. There are studies around which evaluate the accuracy of traceroute-based data, e.g., [40].

The IP-level can be transformed into the AS-level based on an IP prefix to *AS number mapping* .[4] However, a prefix can be announced by multiple ASes, known as the multiple origin AS problem (*MOAS*) [516]. Inferring the AS-level Internet paths from router-level traces is a well-known issue, but still an unsolved problem. In contrast to active measurement, we can infer the AS-level topology by the usage of publicly available data. There are two sources: Internet registries, and BPG routing services. Routing registry information is based on data which is provided by the ISPs and may be incomplete or obsolete. Typically, this information is used to enhance other sources. AS topology information can also be derived from *BGP* routing table dumps and updates, route servers, and looking glasses. A *route server* is member of the BGP peering. It provides limited telnet-access to query BGP routing information. A *looking glass* is basically a web interface that acts as telnet-wrapper for route servers. An offline version of *BGP tables* provide BGP dumps. Projects such as RouteViews[5] globally distribute route collectors, which periodically store snapshots of the BGP table. To reconstruct routing changes, this is done in combination with a dump of all BGP updates obtained between current and preceding snapshot. BGP updates can also be used to include fluctuating, e.g., backup links [514]. It is worth noting that the peering with a route server is voluntary. There are several route servers, which may have different views on the *BGP topology* . BGP tables are location dependent. Consequently, the set of information will be merged.

There are two popular IP traceroute projects, *CAIDA* [6] and *DIMES* [419]. In contrast to CAIDA, DIMES establishes vantage points at end user systems, similar to SETI@home, and thus collects data from significantly more Internet perspectives (i.e., ASes). For a comparison of both data sets we refer to [481]. As mentioned before there are objections to derive the AS

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[4] See `http://www.team-cymru.org/Services/ip-to-asn.html`, for example.

[5] `http://www.routeviews.org/`

[6] Actually, CAIDA is an organization that operates several measurement projects, e.g, Ark (formerly Skitter).

Data Source	Granularity	URL
DatCat	–	`http://www.datcat.org`
CAIDA	AS, IP(, Router)	`http://www.caida.org/projects/ark`
DIMES	AS, IP, Router	`http://www.netdimes.org`
RIPE RIS	AS	`http://www.ripe.net/ris`
RouteViews	AS	`http://www.routeviews.org`
UCLA	AS	`http://irl.cs.ucla.edu/topology`
NEC	AS	`http://topology.neclab.eu`

Table 22.2: Selection of sources for periodically updated measurement data

graph from traceroute. The *RouteViews* project as well as the *RIPE Routing Information Service (RIS)* , for example, provide *BGP* table dumps. The routing table dumps must be post-processed to generate AS relations. The Internet Topology Collection of the UCLA incorporates these both sources, and additional route servers and looking glasses to provide a merged data set on a daily base. Based on the processing of BGP updates, the created AS graph is particularly aware of backup links, which are not visible in the snapshots of BGP routing tables [514]. The project annotates the graph with AS relationships. A simplified AS graph based on RouteViews, RIPE RIS, and UCLA data, is calculated within the project of NEC [498]. It represents an unweighted and weighted next hop matrix, a shortest path calculation (using policy-free and weighted edges), and classifies the ASes in three tiers.

The Internet Measurement Data Catalog (*DatCat*) [418] indexes Internet measurements in a broader context. It does not only include Internet network topologies, but also DNS traces, P2P measurements, etc. It facilitates searching for and sharing of data among researchers. DatCat is a comprehensive database, which is freely accessible by the research community in the context of Internet measurement to allow for reproducible data.

All data sources are summarized in Table 22.2.

22.5.3 On Internet Topology Properties

Although the real Internet structure is unknown in absent of a complete Internet map, there has been various work on analyzing the measured portions. One of the most controversial assumptions of the Internet topology is the scaling relations of several properties according to *power laws* . In their seminal work, Faloutsos et al. [140] analyzed the Internet AS-level topology based on RouteViews BGP tables. They observed that the out-degree of a node, the degree distribution, and the Eigenvalue of a graph adjacency matrix follow power laws. The power law exponent has been related to basic graph characteristics (e.g., number of nodes and edges). The authors thus found a very elegant way to describe the evolving inter-domain Internet structure.

Several researchers verified this work [424], [301], and tried to understand the origin of power laws [313]. A common model in this context is the Barabási-Albert model (cf., Section 22.4.4). Inspired by the work of Faloutsos et al., Bu and Townsley [82] empirically analyzed measured Internet topologies. They show that the AS-level topology is a small world graph [488].

Although the observations by Faloutsos et al. have been verified, there are indications contradicting power laws. Chen et al. [98] argue that the derived AS-level topology is not representative for the Internet connectivity as at least $20 - 50\%$ of the physical links are missing. Using an extended data set they show that strict power law relationship does not hold for the node degree distribution. In a subsequent paper, Siganos, Faloutsos et al. [424] reanalyze their initial work [424] based on the extended AS map and reclaim power law observation using linear regression evaluation. A fundamental observation concerning power law relationship of the node degree distribution and sampling biases has been presented by Lakhina et al. [273]. The authors construct a subgraph which is based on a larger structure without any power-law characteristics (e.g., random graph). They show that this subgraph appears to have power-law degree distribution. Thus, an uneven sampling of a non-power law structure may lead to power law properties.

The inner structure of an AS domain with respect to its IP path diversity has been studied by Teixeira et al. [460]. Path diversity measures the number of available routes between two nodes. The analysis is based on real network information provided by the ISP Sprint, and inferred topologies. Teixeira et al. show that approximately 90% of pairs of Sprint's 17 Point-of-Presence (PoPs) in the US exhibit at least four link-disjoint paths, and that 40% of pairs are linked by eight or more routes. In contrast to this, the topologies derived from active measurements overestimate the number of disjoint paths.

The routing behaviour between two end hosts has been initially analyzed by Paxson [356]. Employing network probe daemons distributed over 37 Internet hosts located in 34 different stub networks, Paxson measured that about 30% of the site pairs cross at least one different AS in the forward or reverse path, and approximately 50% visited at least one different city. For further work on this topic see, for example, [198].

Routing on the AS-level structure depends on the Autonomous System relationships . They determine routing export and selection policies. Links between AS domains are classified in (1) provider-to-customer, (2) customer-to-provider, (3) peer-to-peer, and (4) sibling-to-sibling relationships [173]. No transit traffic is allowed along peer-to-peer-links, and ISPs typically prefer customer routes over peering or provider links. Following specific policies, which are bound to the relation type, realistically chosen AS paths (measured in router hops) are elongated in contrast to shortest path routing. Neglecting inter-ISP relationships and using a simplified shortest AS path policy model, Tangmunarunkit et al. [455] analyzed that 20% of Internet paths are inflated by more than 5 router-level hops. In their subsequent work, the authors ex-

Generator	AS-level	Router-level	Hierarchy	URL
GT-ITM	Yes	No	Yes	`http://www.cc.gatech.edu/projects/gtitm`
Inet	Yes	No	No	`http://topology.eecs.umich.edu/inet`
BRITE	Yes	Yes	Yes	`http://www.cs.bu.edu/brite`
IGen	No	Yes	Yes	`http://www.info.ucl.ac.be/~bqu/igen`

Table 22.3: Network topology generators

tended the policy model but observed that 96% of paths still have the same length independently of the model in use [454]. Based on a routing policy model that reflects commercial relationships, Gao et al. [174] derive the path elongation in AS hops. More than 45% of all AS paths are inflated by at least one AS hop.

22.5.4 Topology Generation

A standardized Internet topology cannot be provided as long as the Internet structure is not completely understood. One may import real measurement data (cf. Section 22.5.2) into the simulator but the created topology remains incomplete (e.g., missing peering links at the AS-level [41], [199]). Additionally, for most simulators the inferred number of nodes and links is too large. Krishnamurthy et al. [267], for example, introduce a sampling method in order to reduce the graph size on the one hand, and preserve power law metrics and slope on the other hand. The created structure is an undirected graph at the AS level. To allow for realistic inter-domain routing, edges need to be annotated with AS relationships as included in some measurement data [514], [498].

There are several network generators available to create synthetic topologies (cf. Table 22.3). One of the first well-established generators was GT-ITM . It provides flat random graphs, and a hierarchical transit-stub model to reflect the AS structure. Inet-3.0 is also an Autonomous System level Internet topology generator. It creates a random network and tries to reproduce inter-domain properties based on the input parameters: number of nodes, and the fraction of degree-one nodes. The characteristics are similar to Internet observations between November 1997 and February 2002 [497]. The authors mention that the model does not represent the Internet well with respect to clique and clustering properties. A topology generator that reflects the Internet AS-level and router-level is BRITE . BRITE is suitable for large scale power law graphs. It uses the *Waxman* , two *Barabási-Albert* *models* , and the generalized preference model to create flat AS, flat Router, and hierarchical topologies. BRITE also implements several import and export schemes to transform graphs between different topology generators and simulators. BRITE, and GT-ITM are pure degree-based generators. More recently, the IGen generator has been introduced that attempts to create end-to-end paths. IGen follows a new generation approach, which includes network design heuristics and geographic restrictions.

22.6 Conclusion

The network topology represents the interconnection of communication entities. It describes the paths which information can flow, and may largely affect evaluation of communication protocols. Understanding existing structures, such as the Internet, is a prerequisite to model realistic topologies. The specification of a graph can be generally descriptive based on a sufficient set of properties, or constructive using generation rules. A constructive creation may again be distinguished in two different approaches: Pure algorithmic construction that defines the procedures to create a graph with specific properties independent of the actual reasons, derived from the network. In contrast, a causality inspired construction models the understanding of the graph evolution as synthesizing the underlying network building process. It is worth noting that the two construction mechanisms follow orthogonal perspectives and may lead to unwanted results when mixed without care.

In this chapter, we introduced basic background on topology modeling, in which we focused on fixed networks. We started with the first modeling step: the abstraction of the real network by a graph, which includes the elimination of unnecessary details. Subsequently, we discussed essential metrics to describe a graph, and to analyze existing structures. The presented examples are not complete, but should be considered as starting point. The selection of metrics and the understanding of their interplay with the subject of investigation are an important part in the modeling. After characterizing graphs, we introduced common topology models. All of them are not directly applicable to the Internet topology, as Internet connections are neither built by random, nor do they follow simple geometric or preferential attachment rules. We discussed Internet topology modeling in the last section.

The modeling of the Internet is an intricate task. First and foremost, we are not able to capture the complete Internet, and thus there is no complete understanding of its structure. There are measurement projects. Processing their output (e.g., merging different sources) can be part of the modeling. Presenting an Internet topology without mentioning its level of granularity (i.e., AS-, router-, or IP-level) is meaningless. Recent discussions [193] advise to enrich the topology generation by some level of randomness to reflect the various evolutionary aspects of the Internet.

Subsequent steps may include the modeling of the network layer (Chapter 16), augmenting connections by corresponding link delays (Chapter 19), and the evaluation of protocols based on realistic traffic patterns (Chapter 18). For an in-depth treatment of network topologies in the context of communication networks, we refer to the excellent books [69], [122], and [471].

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