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Design of Interactive Visualizations for Next-Generation Ultra-Large Communication Networks

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ABSTRACT With the increasing size and complexity of next-generation communication networks, it is critical to utilize interactive visualizations to support the monitoring, planning, and management of networks. Effectively visualizing large-scale networks is difficult with traditional methods because of the high link density and complex node relationships. Given the limited screen space, to assist Internet Service Provider's (ISP) network planning and management activities, investigating how to present ultra-large-scale network data efficiently is crucial. This paper presents a real-time interactive visualization system that combines the design strategies of progressive disclosure and multiple panels to elegantly visualize the large-scale networks and avoid the information-overload problem. The system also visualizes the configuration of the network elements and provides the network performance information, including the port-level Quality of Service (QoS) metrics. Furthermore, the system enables navigation through the port-level connection and provides different modes for multiple purposes.

INDEX TERMS Large-scale computer networks, computer network management, quality of service, interactive visualization, human-computer interaction.

I. INTRODUCTION

There has been a rapid growth in both the variety and volume of network traffic. At the same time, it is becoming ever more important for network analysts to understand network behaviors and conduct network management [1]. Network management refers to initializing, monitoring, and modifying the operation of the primary network functions that directly support user requirements. It also refers to the methods, activities, procedures, and tools that pertain to the operation, administration, maintenance, and provisioning of networked systems [2]. Network operators and engineers should be enabled to monitor, measure, and analyze the network ecosystem to keep it healthy as long as possible [3]. Network monitoring and measurement provide valuable information to network administrators, ISPs, and content providers [4]. The concerns about an efficient network and service management have been considered essential for business goals since it is one of the pillars to ensure competitive advantages in the market [3].

In a large-scale network with various equipment, it is vital to understand the physical and logical connections, the hierarchy of equipment, geographical information, and the temporal variance of the network [5]. Some previous research works enable network administrators to retrieve management information from remote devices, analyze the collected data, and take decisions to fix or optimize the network by reconfiguring not well-tuned devices. With the complexity of the context data, more and more researchers consider it essential to allow administrators to shift through massive traffic logs in a visually appealing and interactive manner that encourages data exploration rather than hindering it [6]. In the network management domain, however, the gap between the daily network monitoring and the high level of decision-making is currently not bridged well by the current interactive visualization systems [7]. Visualization, as a tool to help human operators in management tasks, has always been regarded as a research challenge in the area of network management [8].

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Real-time analysis and visualization are worth more attention because of the support of timely response and decision making [9]. It has been stated that visualization in near real-time may improve network administrators' diagnoses and reactions [3]. Dargie and Poellabauer [2] have claimed that the existing visualization techniques and tools do not satisfy the network operators' needs. With the increasing size and complexity of networks, the traditional topological views do not scale well. There is a growing need for online or real-time visualizations to reduce detection and reaction time.

Effectively visualizing a moderately large-scale network has been considered difficult with traditional methods. The density of links is high, and the relationship between nodes is complex. Given the limited screen space, it is essential to explore how to manage large quantities of management data efficiently and view it at a user-defined level of detail. Understanding the network as a whole by visualizing objects' position, their semantics, and relationships in near real-time is a long-term dream of the network operators. The layout and view of topology and the organizing of topology play an important role in network visualization [10]. Early visualizations aimed to understand overall network loads and topology, and recent works focus more on helping network operators and network planners understand the network at different scales [1]. In this case, the interactive features with enhanced usability are mandatory, e.g., zooming, filtering, and details on demand. Various equipment, such as routers, are used in a large-scale network, and the network structure is based on the hierarchical information of the equipment. There remains a research problem of arranging the layout for the large-scale hierarchical data to avoid the information overload problem and also display the necessary details and information. Also, visualizing the network elements only according to the hierarchical data may lose other essential information; for example, it is necessary to explore how to easily determine both the geographic information and the hierarchy information of the network elements [5]. In addition, using inappropriate ways of producing visual representations always results in increased development effort and doubtful results from the user perspective. Besides the layout and interaction, the design of the visual representations also needs careful consideration to better visualize the elements and traffic in the network. Therefore, it can enhance the monitoring and planning ability.

It is essential to provide enough details in the network visualization to help the administrators with their decision making. Quality of Service (QoS) management is an essential task in network service management [11]. QoS monitoring tends to allow network administrators to track the ongoing QoS, compare monitored QoS against expected performance, detect possible QoS degradation, and then tune network resources accordingly to sustain the guaranteed QoS [12]. Besides, with detailed information, the visualization system may not only be utilized for network management but also be beneficial for network planning. Network planning is concerned with the cost-effective deployment of a communication infrastructure to provide adequate throughput, coverage, and quality for the end-user services [13]. The network planners could use interactive visualization systems to aid in capacity planning since the network congestion points can be easily identified.

Given details of the ultra-large-scale network topology, real-time network configuration, and details of QoS parameters, the research goal is to develop an interactive visualization system for planning and monitoring such a large-scale communication network that would support the following features:

- visualize the ultra-large-scale communication networks and avoid the information-overloaded problem;
- visualize the configuration and the inside structure of routers, and port level QoS metrics;
- navigate between the linked nodes and ports in the communication network;
- provide different modes to identify the capacity, anomaly, and the quality degradation in the network;
- provide visual elements (data) filtering and generate the data managed file for future use;
- visualize the communication network in real-time for monitoring purposes.

In this paper, we propose a design for a real-time interactive visualization system that combines the design strategies of progressive disclosure with the semantic zooming techniques and multiple panels to visualize the large-scale network elegantly. The system also visualizes the configuration and the inside structure of the network elements and provides the network performance information, including the port-level Quality of Service (QoS) metrics, thus enabling the network planners/network managers to conduct their network health analysis more effecitively. In addition, the system enables navigation through the port-level connection and provides different modes for multiple purposes. Compared with previous research works, this system can clearly visualize the large-scale network in real-time and display enough details efficiently. Also, the users will not lose the context of the connection and condition information during the exploration. Additionally, the system provides the data filtering feature and different modes, including the normal and alert modes, which benefit users in planning and monitoring the large-scale communication network. This system could improve diagnoses and support decision making. It also improves users' response time and speeds up identifying the trouble to better solve anomaly problems and conduct health analysis.

This paper is organized as follows: Section II explores and analyzes previous related network monitoring visualization systems. Section III describes the approach and methodology utilized in designing and developing this system. Section IV illustrates the visualization design in detail and Section V introduces the case study to further illustrate how the visualization system can be utilized to solve the task. In Section VI, the conclusion and future work are proposed for further examination and future studies.

II. RELATED WORK

There is a growing need to efficiently visualize large network topologies in the communication network. Communication network management is required to visualize relationships between a large number of network elements, such as the routing relationships between the internet routers. In practice, network administrators need to monitor the network in real-time so that problems due to unusual traffic patterns, equipment failures or misconfiguration can be detected [17]. This raises the problem of how to visualize large network topologies in real-time and provide plenty of useful information for monitoring. There has been a vast amount of work to design different visualization solutions to display the network, e.g., node-link representation [14], [15], [18], fisheye tree [16], [19], treemap [20]–[24], matrix display [25]–[27], circular layout [28]–[31] and parallel coordinate [32]–[37]. It has been widely acknowledged that node and link displays are the most intuitive and effective layouts to visualize the small sparse network for the most purpose [38]. However, there are some problems when visualizing larger networks with the node-link layout. The displays are easily overwhelmed and become cluttered and visually confused when displaying too much information. Also, the running time and processing load of this layout are high. Besides, the interpretation of the layout is dependent on the node positioning, and the different node positioning algorithms lead to quite different interpretations of the data [39]. Many research works have been conducted in order to overcome the limitation of the node-link layout in a large-scale network and proposed the following methods: adopting parameter focusing, zooming techniques, 3D layout, and novel graph modeling.

Visualization has its beginnings as an area between the end of the ’80s and the beginning of the ’90s [3]. The significant evolution with the internet happened years later. The ’90s were characterized by relevant contributions from the AT&T Bell Laboratories team. Many research projects have been conducted in the 1990s. SeeNet system was developed by Becker *et al.* [14], [40] and try to visualize the network with parameter focusing. SeeNet has three complementary graphical techniques to display network data: link map (that represents network connections), node map (that displays nodes by showing a glyph or symbol with characteristics such as size, shape, and color), and traffic matrix (Figure 1-a). Several interactive techniques were integrated into this system, such as manipulating line length between links, symbol size and animation speed, zooming and brushing. The analyst manipulates the display parameters interactively while watching the display change. SeeNet tried to solve the information overload problem through parameter focusing and dynamic interaction. However, this system still cannot handle the large-scale network efficiently.

More research works have been conducted, and the 3D embeddings have been proposed to solve the information-overloaded problem in node-link layout. An approach for large-scale network visualization has been described by Gansner *et al.* [41] from AT&T lab, and it was an experiment with a novel graphical representation of networks using a hierarchy of 3D surfaces that forms a hierarchical graph surface. The 3D layout can solve the link intersecting problem, and therefore, the display is perceived to be less cluttered. With more recent works, Inoue *et al.* [16] proposed a 3D visualization system to display network topology, node information, link quality, and packet flow. For visualization of topology, GPS mode (Figure 1-d) and manual mode were implemented, and the latitude information of the node was provided in the 3D canvas. When dealing with large-scale data, it is not easy for administrators to navigate through the 3D layout. Besides, the interaction techniques are not utilized to display more information. Tateishi *et al.* [5] has proposed a network visualization system MANET using 3-D space and time axes for determining failure points. Instead of displaying geographical information and hierarchical information of topology separately, a visualization method with 3D axes was proposed. Geological information was displayed on an X-Y plane while the hierarchical information of network equipment was displayed on Z-axis (Figure 1-e). The viewpoint and direction could be freely selected in a 3D view. Though this visualization enables administrators to determine failure points and affected areas at a glance, the visualization will still be confusing with human’s cognitive workload when it involves the large-scale data. In addition, it does not visualize various types of data, like network performance information and router information, in a complicated way. Overall, the difficulty with the 3D network display is that they are often tricky and confusing to navigate, which may cause the user to lose the sense of the overall context.

In order to overcome the limitation of node-link layout, some recent research works continue to explore the layout of visualizing complex networks and try to use multiple layers or multiple views to represent and visualize the network. Hofstede and Fioreze [15] created a monitoring system SURFmap to provide traffic information at a geographical dimension by using the Google Maps API (Figure 1-b). Interactive zooming and details-on-demand techniques were applied to this system. Though SURFmap added a geographical dimension to network data, it lost some other network information, like the network performance information, was not integrated into the visualization. In addition, though it provided four zoom levels including country, region, city, and host levels to arrange the network data, the context of data in higher hierarchical zoom level and hierarchy information of network will be lost. Wang [10] described a visualization prototype system for large-scale and complex networks. Organizing the large topology into multiple layers has been suggested. The system provides a visual representation of network topology, device information, connection information, and monitoring messages. Though the visualization system provides a satellite view for users to find which part of the whole topology map is now in their view (Figure 1-c), the visualization will lose the context when switching between different views. In addition, the system has not integrated with network performance

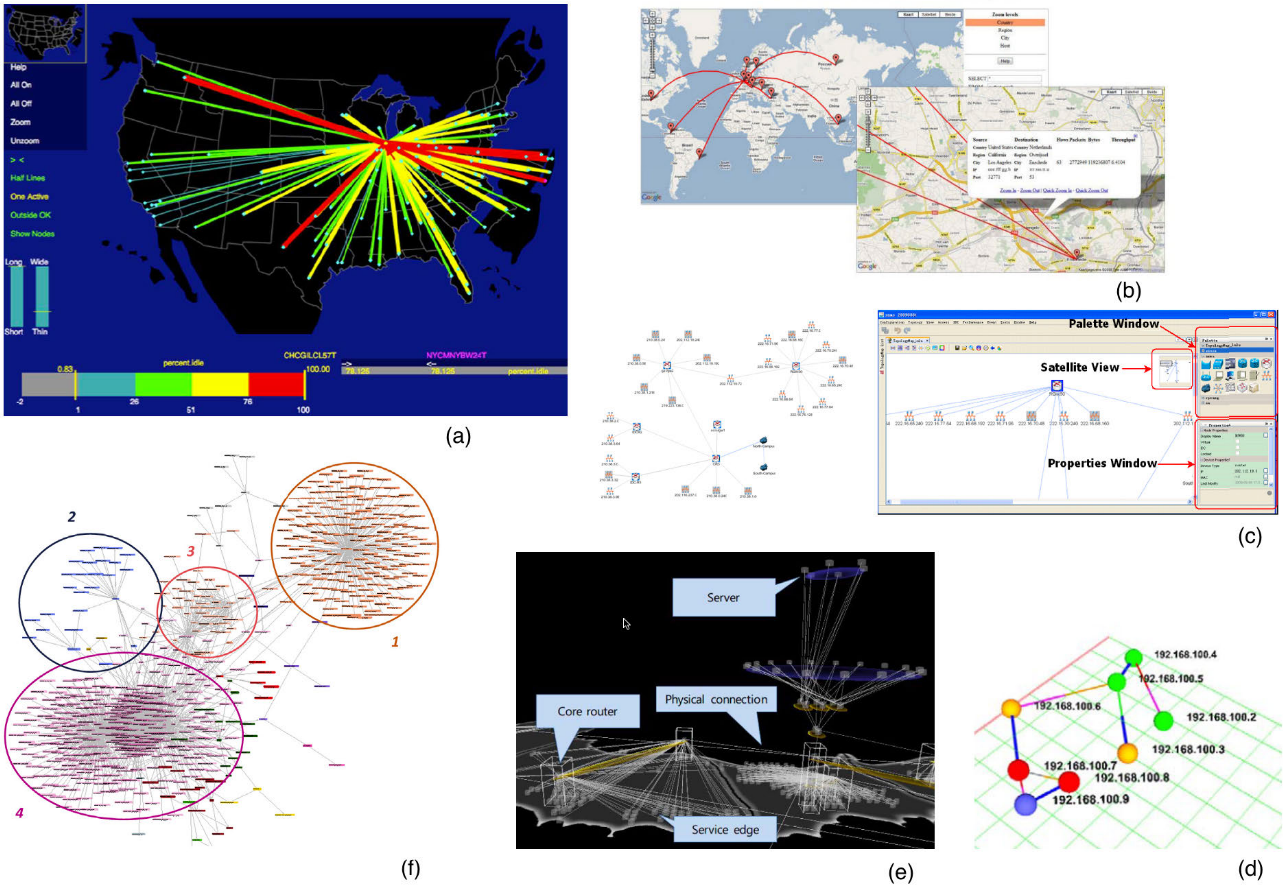


FIGURE 1. (a). An overview of SeeNet visualization [14]; (b). The screenshots of the DNS attack in country zoom level and host zoom level in SURFmap [15]; (c). A top-layer overview of a complex network and a prototype GUI with Satellite View, Palette Window and Properties Window highlighted [10]; (d). The GPS mode (3D) in MANET [16]; (e). The example of displaying physical connections [5]; (f). A cluster view (different colors represent different clusters) using the Walktrap algorithm. The cluster visualization helps in understanding the communities [6].

monitoring, and the visualization is not real-time. Though this visualization still does not perfectly visualize the large-scale network for monitoring purposes, it provides us with the idea to organize a large and complex topology into multiple layouts. The top layer only reveals the most crucial structure of the topology, and the lower layers contain more details of the network.

Some novel techniques, including the machine learning algorithms, have been explored to augment human investigators' domain knowledge and therefore reduce the workload of the visualization system. Liao *et al.* [6] developed a system called ENAVis, which offers visual analysis features including connectivity graphs of combinations of hosts, users, and applications. The visualization system was implemented through the use of dynamic correlation and novel graph modeling. As has been claimed by Liao *et al.* [6] that it is vital to determine the set of variants and invariants of the network graphs, the maximum common subgraph, and the minimum common supergraph are visualized. The Walktrap algorithm is also selected as it takes the random walk approach for graph cluster visualization, as represented in Figure 1-f. The system is also integrated with the graph mining process to maximize the knowledge/insight acquisition. All these algorithms and methods can guide the visual exploration process to only essential things.

Some architectures and designs were introduced to addressing real-time visualization for further guidance. Parulkar and Schmidt [42] introduced the architecture of a visualization system that is configurable and can support multiple simultaneous real-time displays of a network. They presented a design for the visualization system called View Choreographer, which filtered the events to present and perform user-specified mappings of network events. A real-time system on Android terminals for visualizing network topology and packet flow in the network has been designed by Tsutsui [43] to conduct efficient MANET field experiments. Fuji *et al.* [44] presented an approach to visualize networks in real-time with a bifocal display technique. Though the visualization simultaneously displays both context and local details within a single window without the loss of information, it is still not suitable for ultra-large-scale network data.

The above research tried to overcome the limitation of the node-link layout in a large-scale network by adopting parameter focusing, zooming techniques, 3D layout, or novel graph modeling. However, there still exist some problems with these methods. Some visualization systems may lose the context or be confusing to navigate. Others may not be able to contain enough details or visualize the large-scale network data efficiently. Therefore, these previous works have motivated us to better visualize the large-scale network data and provide enough low-level details, thus enabling the network administrator to plan and monitor the next-generation communication network efficiently. Our work proposes a design of the real-time interactive visualization system that combines the design strategies of progressive disclosure with the semantic zooming techniques and multiple panels to elegantly visualize the large-scale network according to its hierarchy and avoid the information-overloaded problem. In this way, the whole network will be partially visualized in different panels, and the users still do not lose the context during exploration. The system also visualizes the configuration and the inside structure of the network elements and provides the network performance information, including the port-level Quality of Service (QoS) metrics. The low-level information could benefit the network planners/network managers in conducting their network health analysis in a more effective way. In addition, the system enables navigation through the port-level connection and provides different modes for multiple purposes.

III. METHODOLOGY AND SYSTEM DESIGN

The client-server architecture has been adopted in this system, and the system design configuration is illustrated in Figure 2. There are three layers in the system architecture: the storage layer, back-end layer, and the visualization layer (front-end layer). The information stored in the storage layer is discussed in detail later in this section. The server is implemented to retrieve the data from the storage layer and continuously generate and publish new network data to the visualization layer. The users interact with the visualization system at the visualization layer to explore and monitor the network. The users can also input some numbers and select the attributes to display the user-defined range of data elements. The visualization layer will send the query to the server. After the server receiving the request, the server will filter the data according to the query range and then save the filtered data files for management purposes.

Our visualization system is required to visualize the real-time network data, and the users can also interact with the system and send queries to the server. Therefore, besides continuously sending the data to the visualization layer, continuous and full-duplex communication between the server and the visualization layer is required. Due to this reason, WebSocket has been applied in this real-time visualization system. WebSocket enables interactive, event-driven communication, facilitating real-time data transfer between client and server over a single TCP connection. The WebSocket protocol supports transferring messages between a web client and a web server in any direction. It offers a standardized way for the server to send messages to the client without being first requested by the client, and allowing messages to be passed back and forth while keeping the connection open [45]. It is designed to be implemented in web browsers and web servers, but it can be utilized by any client or server applications. The server side runs on a 2.3 GHz Intel Core i5 macOS machine with 16 GB 2133 MHz LPDDR3 memory that can handle a large amount of processing in a quick time. It is implemented using Python, and the Tornado library is utilized. Tornado is a python web framework and asynchronous networking library [46]. By using non-blocking network I/O, Tornado can scale to tens of thousands of open connections.

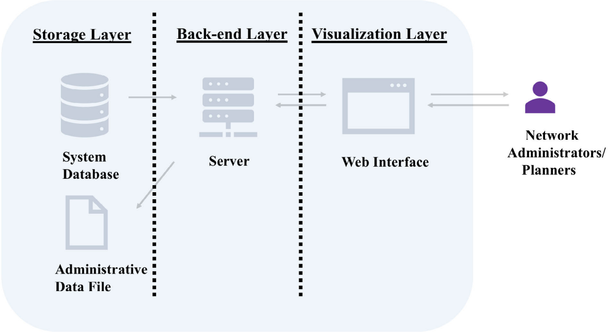


FIGURE 2. The system design configuration architecture.

In order to provide easy access to network management, the network visualization system would be developed as an interactive web tool. The creation of a browser-based system can be utilized as a generalized presentation layer for network management and planning applications. The client application of our system is an SVG enabled web browser that connects to the server and retrieves information from the server. The visualization layer is built with D3.js and Bootstrap. D3.js facilitates mapping the processed data into visual representations and allows users to bind arbitrary data to a Document Object Model (DOM) and then apply data-driven transformations to the elements. The D3.js library is widely adopted among the network visualization tools and speeds up the development process [47]. The Bootstrap library can help to style the elements of the page consistently and appealingly. It contains CSS and JavaScript-based design templates for forms, navigation, buttons, and other interface components.

Instead of collecting, structuring, and transferring data, simulated network data is applied to the visualization system at this stage. The simulated structured data is generated through the following process: selecting a structure of the data; using the random number generator to generate a sample from the assumed structure; formatting the simulated data. There are mainly two data collections to be visualized in this research: the network topology information and the router detail information. The network topology information includes the link configuration that displays the communication in the network and the link utilization information. The router detail information stored the router configuration information including the condition of power, chassis, processor, etc., and also the slot information and port information. The

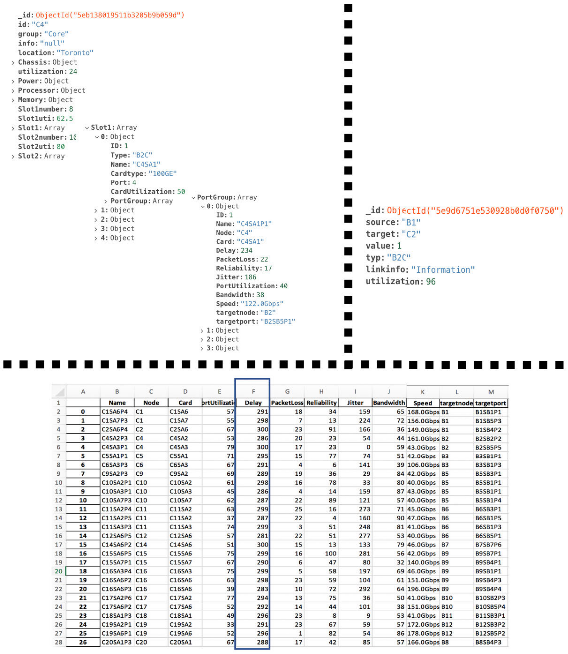
TABLE 1. **The data range for the simulated configuration information of the edge router.**

	Config	Card Type	Total Ports	Slot Utilization (%)	Port Utilization (%)	Port bandwidth (%)
Chassis	Standard					
Memory	Standard					
Processor	Dual					
Power	Dual					
Access facing slot	10			50-90		
		10Mbps	10		50-80	50-90
		100Mbps	10		50-80	50-90
		GE	20		50-80	50-90
		10GE	20		50-80	30-90
		40GE	10		50-80	30-90
Core facing slot	10			50-90		
		GE	10		50-80	50-90
		10GE	10		50-80	30-90
		40GE	6		30-80	30-90
		100GE	4		30-80	30-90

router detail data also includes the utilization information of each router and the QoS metrics of each port. The detail of the structure and the data range for each attribute will be described as follows.

This project tends to simulate the topology of routers' connection in the real-life situation. The Cisco hierarchical internetworking model has been widely adopted in the industry for designing a flexible, scalable, and reliable network [48]. Compared with the flat network design, broadcasts can be easily controlled, and undesirable traffic can be efficiently filtered with the hierarchical design. The access layer, distribution layer, and core layer are all visualized in our system, and also, the information of border/ gateway routers that connect a specific network (i.e., ISP) to another network or ISP will be included as well. The percentages of each type of routers are structured to simulate the real-life situation, and the structure and number of the connections between different hierarchical routers are also designed according to the industry standards. The whole topology of the network is a partial mesh, which means routers are much more tightly coupled than in any of the basic topologies but are not fully interconnected. A partial mesh can reduce the startup and operational expenses by not interconnecting low-traffic segments. Therefore, the partial mesh is more scalable and affordable than a full mesh topology.

In order to facilitate the generating process of the simulated data, we referred to some databases [49]–[51] that provide router utilization and QoS metrics data, and explored the information of the routers that are in daily use in industrial application. According to these data examples, we settled some standards for each type of routers and defined the range for the slot utilization, port utilization, and port bandwidth. The data range for the simulated configuration information of the edge router is illustrated in Table 1 as an example. To simulate the QoS performance data of the ports, the range for each QoS metric is defined. The data range is determined for generating the simulated test data to examine the visualization system. It is only used for facilitating the simulated network data generating process, and the real-world data could be within different data ranges. The data is generated using the Random module in Python and the random integers are from the discrete uniform distribution. With the simulated network data, we could operate our proposed visualization system experimentally and confirm its effectiveness. All the data examples are represented using JavaScript Object Notation (JSON). It can be noticed that in Figure 3-a, in the router detail collection, the port data is embedded into the slot object, and the slot object is embedded into the router node. The QoS information of each port, including the delay, packet loss, reliability, jitter, and bandwidth information, is stored. The right part in Figure 3-a is an example of data in the network topology collection, and the data includes the source information, the target information, and the link utilization information.



```
 _id: ObjectId("5eb138019511b3205b9b059d")
 id: "C4"
 group: "Core"
 info: "null"
 location: "Toronto"
› Chassis: Object
 utilization: 24
› Power: Object
› Processor: Object
› Memory: Object
 Slot1number: 8
 Slot1uti: 62.5
› Slot1: Array
 Slot2number: 10
 Slot2uti: 80
› Slot2: Array
```

```
⌄ Slot1: Array
  ⌄ 0: Object
      ID: 1
      Type: "B2C"
      Name: "C4SA1"
      Cardtype: "100GE"
      Port: 4
      CardUtilization: 50
    › PortGroup: Array
  › 1: Object
  › 2: Object
  › 3: Object
  › 4: Object
```

```
⌄ PortGroup: Array
  ⌄ 0: Object
      ID: 1
      Name: "C4SA1P1"
      Node: "C4"
      Card: "C4SA1"
      Delay: 234
      PacketLoss: 22
      Reliability: 17
      Jitter: 186
      PortUtilization: 40
      Bandwidth: 38
      Speed: "122.0Gbps"
      targetnode: "B2"
      targetport: "B2SB5P1"
  › 1: Object
  › 2: Object
  › 3: Object
```

```
_id: ObjectId("5e9d6751e530928b0d0f0750")
source: "B1"
target: "C2"
value: 1
typ: "B2C"
linkinfo: "Information"
utilization: 96
```

	A	B	C	D	E	F	G	H	I	J	K	L	M
1		Name	Node	Card	ortUtilizati	Delay	PacketLoss	Reliability	Jitter	Bandwidth	Speed	targetnode	targetport
2	0	C1SA6P4	C1	C1SA6	57	291	18	34	159	65	168.0Gbps	B1	B1SB1P1
3	1	C1SA7P3	C1	C1SA7	55	298	7	13	224	72	156.0Gbps	B1	B1SB5P3
4	2	C2SA6P4	C2	C2SA6	67	300	23	91	166	36	149.0Gbps	B1	B1SB4P2
5	3	C4SA2P3	C4	C4SA2	53	286	20	23	54	44	161.0Gbps	B2	B2SB2P2
6	4	C4SA3P1	C4	C4SA3	79	300	17	23	0	59	43.0Gbps	B2	B2SB5P5
7	5	C5SA1P1	C5	C5SA1	71	295	15	77	74	51	42.0Gbps	B3	B3SB1P1
8	6	C6SA3P3	C6	C6SA3	67	291	4	6	141	39	106.0Gbps	B3	B3SB1P3
9	7	C9SA2P3	C9	C9SA2	69	289	19	36	29	84	42.0Gbps	B5	B5SB3P1
10	8	C10SA2P1	C10	C10SA2	61	298	16	78	33	80	40.0Gbps	B5	B5SB1P1
11	9	C10SA3P1	C10	C10SA3	45	286	4	14	159	87	43.0Gbps	B5	B5SB1P1
12	10	C10SA7P3	C10	C10SA7	62	287	22	89	121	57	40.0Gbps	B5	B5SB1P4
13	11	C11SA2P4	C11	C11SA2	63	299	25	16	273	71	45.0Gbps	B6	B6SB3P1
14	12	C11SA2P5	C11	C11SA2	37	287	22	4	160	90	47.0Gbps	B6	B6SB1P5
15	13	C11SA3P3	C11	C11SA3	74	299	3	51	248	81	41.0Gbps	B6	B6SB1P3
16	14	C12SA6P5	C12	C12SA6	57	281	22	51	277	53	40.0Gbps	B6	B6SB5P1
17	15	C14SA6P2	C14	C14SA6	51	300	15	13	133	79	46.0Gbps	B7	B7SB7P6
18	16	C15SA6P5	C15	C15SA6	75	299	16	100	281	56	42.0Gbps	B9	B9SB7P1
19	17	C15SA7P1	C15	C15SA7	67	290	6	47	80	32	140.0Gbps	B9	B9SB4P1
20	18	C16SA3P4	C16	C16SA3	75	299	5	58	197	69	46.0Gbps	B9	B9SB1P1
21	19	C16SA6P2	C16	C16SA6	63	298	23	59	104	61	151.0Gbps	B9	B9SB4P3
22	20	C16SA6P3	C16	C16SA6	39	283	10	72	292	64	196.0Gbps	B9	B9SB4P4
23	21	C17SA2P6	C17	C17SA2	77	294	13	75	36	50	41.0Gbps	B10	B10SB2P3
24	22	C17SA6P2	C17	C17SA6	52	292	14	44	101	38	151.0Gbps	B10	B10SB5P4
25	23	C18SA1P3	C18	C18SA1	49	296	23	8	9	53	41.0Gbps	B11	B11SB3P1
26	24	C19SA2P1	C19	C19SA2	33	291	23	67	59	57	172.0Gbps	B12	B12SB3P2
27	25	C19SA6P1	C19	C19SA6	52	296	1	82	54	86	178.0Gbps	B12	B12SB5P2
28	26	C20SA1P3	C20	C20SA1	67	288	17	42	85	57	166.0Gbps	B8	B8SB4P3

FIGURE 3. **(a) The network data example (upper); (b) The generated filtered data file as the QoS report (down).**

When the network administrators and planners interacting with the visualization system, they can input some numbers and select the attributes to display the user-defined range of data elements. The visualization layer will send the query to the server. The server will filter the data according to the query range and then save the filtered data files as the QoS report for management and planning purposes. The filtered data are saved as the excel files, and an example of the part of the report is shown in Figure 3-b. The report represented in Figure 3-b is generated to list the ports whose delay is higher than 280 milliseconds. The port information which includes the port ID, the ID of the router the port located in, the line card ID, the QoS information of the port, and the ID of the target router and target port is recorded in the report to support the management and future planning. The port's ID is defined by combining the ID of the line card and its position in the line card. The line card's ID is composed of the ID of the router and its position in the line card. The 'SA' in the ID means the line card slots are dealing with the incoming packets, and the 'SB' means the line cards perform the output function.

IV. VISUALIZATION SYSTEM DESIGN

When visualizing large-scale network data for monitoring and planning purposes, the complexity of network architecture and large-scale data are the major issues. Analyzing the overall network properties might be too coarse to be useful for network management. Identifying and locating faults naturally becomes more difficult with large and more diverse networks. Presenting the complex network data into simple visualization is a significant challenge. Instead of using parameter focusing or 3D embeddings to solve the information overload problem in large-scale network visualization, our visualization is designed to combine the design strategies of progressive disclosure and using multiple panels to cleverly position nodes to show the network structure.

Progressive disclosure is an interaction design technique to help maintain a user's attention by reducing the cognitive workload. It improves usability by presenting only the minimum data required for the task at hand. Progressive disclosure can limit what is shown on a screen and only show users what they need when they need it. A hybrid to progressive disclosure called staged disclosure was introduced by Nielsen [52], characterized by the back-next(wizard) interaction technique. It is a step-by-step process that allows users to input information in a prescribed order and in which subsequent steps may depend on information entered in the previous one. However, the wizard method is not gracefully interruptible, and if the users quit the process midway, they might not only lose their work but also may need to click again through the preceding steps. Even though sometimes the wizard support saving of the state and resuming later, it is not easy for users to recover the context and the mental model of the process. Therefore, our visualization is designed with multiple panels to show each state of the visualization. In this way, the visualization system provides the context and more information than considering each component independently.

In order to conquer the problem of the overload information problem, the design of our visualization divides the network according to its hierarchy and visualizes it separately in different panels. Combined with the interaction techniques, the users can interact with the system and only explore the part of the network they are interested in or the elements where some anomaly activities may exist. Clicking the selected node and its lower level linked nodes will appear in the next panel. In this way, the large-scale data can be divided and only be shown separately with some interaction. If every panel could support to visualize N nodes in a delectable layout and manner, and the visualization has q panels, the order of magnitude of the data the system can support is N^q. Thus, large-scale data can be managed to be visualized elegantly and also not lose the context.

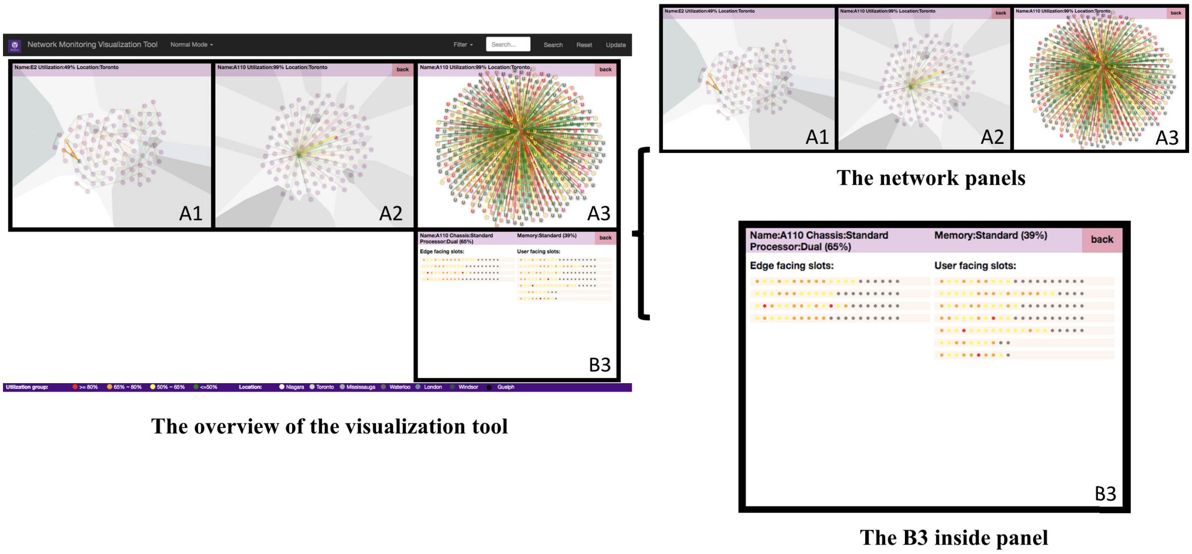
Multiplicity of interactions is essential for exploring complex visualizations [53]. Some interaction techniques were selected to be utilized in this visualization system to facilitate mental processing needs and assist in users' discourse with the network data. Brushing is a change in the encoding of one or more items essentially immediately following and in response to an interaction with another item [54]. The intention of brushing is to highlight brushed items in different views of a visualization. The details-on-demand technique is also selected to facilitate the exploration of the network, and semantic zooming is a form of details-on-demand that lets the user see different amounts of details in a view by zooming in and out. Semantic zooming is usually a combination of two epistemic actions: drilling and transforming. It could provide the user with the ability to act upon the visualization to bring more information to the surface and to manipulate the semantic and geometric properties of the visualization. Semantic zooming adjusts the contents and density of information that is shown instead of only changing visual detail and scale. Details of the design of the visualization system will be described in the following sections.

A. OVERVIEW

The whole visualization can be divided into two types of panels: the network panel (A1, A2 and A3 in Figure 4) and the inside panel (B3 in Figure 4 and B1 and B2 are hidden). The network panels are arranged in the upper position, and the inside panels are in the lower position. There are three network panels and three inside panels. The overall network information and condition are visualized in the network panel. As shown in Figure 4, the A1 panel visualizes the whole border routers, core routers, and edge routers in the network. The A2 panel only visualizes the selected edge router and its linked access routers. The A3 panel visualizes the selected access router and its linked users. Each inside panel visualizes the inside router configuration information and the port-level QoS metrics of the selected router. Some buttons, drop-down menus, and filtering form are at the top of the page. The legend, which indicates the color encoding of this visualization system, is placed on the bottom of the page for better-supporting users' exploration.

B. THE NETWORK PANEL

The elements of visualization in the network panels are as follows. The glyph is made up of a circle and a letter to represent each router. The letter comes from the initials of the type of routers. The router type that each letter stands for are as follows: Border routers are represented as B; Core routers are represented as C; Edge routers are represented as E; Access routers are represented as A, and User routers are represented as U. The nodes are connected with links and links are represented as lines in our visualization. The nodes or links' color indicates the current utilization of the nodes



Name:E2 Utilization:49% Location:Toronto

Name:A110 Utilization:99% Location:Toronto

Name:A110 Utilization:99% Location:Toronto

Name:A110 Chassis:Standard Processor:Dual (65%)

Memory:Standard (39%)

Edge facing slots:

User facing slots:

Utilization group: ● >= 80% ● 65% ~ 80% ● 50% ~ 65% ● <=50%

Location: ● Niagara ● Toronto ● Mississauga ● Waterloo ● London ● Windsor ● Guelph

FIGURE 4. The system design configuration architecture.

or the links, and they are with the same color encoding. The network administrators/planners are only concerned about the range that the utilization falls to and not the specific value. Therefore, in our visualization system, the quantitative utilization data are categorized into different levels, and the different utilization groups are encoded with different colors. Due to the monitoring purpose, the green color indicates the 'healthy' nodes or lines of which the utilization is below 50%, and the red color alerts the users that the nodes or links are under a heavy workload so that some actions may need to be adopted to fix this issue. The specific color encoding design for the nodes and links are as follows: the green color shows that the utilization is below 50%; the yellow color shows that the utilization of this node or link is larger or equal to 50% and smaller than 65%; the orange color shows that the utilization of this node or link is larger or equal to 65% and smaller than 80%; the red color shows that the utilization of this node or link is larger or equal to 80%. Such color encoding could aid network administrators and planners to easily identify where the utilization achieves the high level and consequently worsens the network performance. The legend that indicates the color encoding of the utilization group is also provided in the visualization system to aid in monitoring and planning.

Instead of using other layouts, for example, matrices or tree layout, the force-directed graph is selected to display the layout since it is more direct and intuitive. The force-directed layout produces a visually meaningful layout: nodes with more direct or indirect neighbors tend to find themselves closer in the layout. The nodes and links are organized in the force-directed graph layout using Verlet integration to allow simple constraints. Verlet integration is a numerical method used to integrate Newton's equations of motion, and it is generally utilized to calculate trajectories of particles in molecular dynamics simulations [55]. It assumes a constant unit time step $\Delta t = 1$ for each step, and a constant unit mass $m = 1$ for all particles. Correspondingly, a force F acting on a particle is equal to a constant acceleration a over the time interval Δt. It can be simulated by adding to the particle's velocity, which is added to the particle's position afterward. This implementation also utilizes a quadtree to accelerate charge interaction using the Barnes–Hut approximation [56]. Both the repulsive charge force and a pseudo-gravity force are applied among the nodes. The pseudo-gravity force keeps nodes centered in the visible area and avoids expulsion of disconnected subgraphs, while links are fixed-distance geometric constraints. In addition, the force is customized to place the nodes in the same location together in the visualization and set apart nodes that are geographically away.

The background areas of the nodes indicate their location. The Voronoi diagram is utilized to partition the plane into regions close to each of a given set of objects. The Voronoi diagram partitions the space based on the minimal distance to each site. Let $P = p_1, \ldots, p_n$ be a set of n distinct points, called sites, and let $d(p, q)$ be the Euclidean distance between points p and q. The first order Voronoi diagram of P is a subdivision of the plane in n cells, one for each site in P, such that a point q lies in the cell of a site p_i if and only if $d(q, p_i) < d(q, p_j)$ for all sites $p_j \in P$ with $j \neq i$ [57]. The cell boundaries lie on the perpendicular bisectors of the line segments $p_i p_j$ [57]. Visualizing the diagram is straightforwardly done by drawing the set of disjoint, adjacent planar polygons that represent the diagram [58]. The different location areas are represented using different levels of grey color. As shown in Figure 4, the legend that indicates the color encoding of the nodes' location is displayed at the bottom right of the page to directly support the exploration of the visualization. In this way, it is intuitive to determine both the hierarchical and geographical positions of the routers.

C. THE INSIDE PANEL

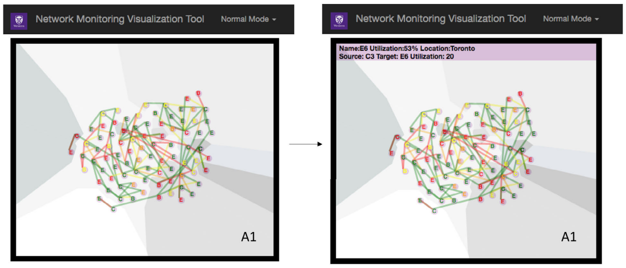
The inside panel visualizes the inside information of the router, and it is demonstrated in Figure 4. The rectangles represent the line cards, and as the inside structure of routers, the line cards are divided into two slots. Each slot faces different levels of routers. As the routers' hierarchy, border routers' ports only connect with core routers, and the user routers only connect with the access routers. Other routers each have two slots, and the ports in these two slots link to an upper and lower hierarchical level of routers respectively. In our visualization, the ports are represented as circles, and they are placed on the rectangles that represent line cards. The color of the ports also encodes the utilization of the port and they have the same encoding with the nodes and links' utilization. The grey ports depict that the ports are not in utilization. The concrete information of the router has been shown on the top of the panel which includes the name, the chassis type, the memory type, the memory's utilization, the processor type and processors' utilization.

D. INTERACTION

It is widely recognized that a large part of the usefulness of a network management system lies in its interactivity. The element of interactivity is basically defined as the ability to respond to actions and dynamically change graphical representations. Interactivity is the very element that generally makes the difference between a real usable application and a mere depiction [34]. The design and development difficulty is that the implementation of interactivity incorporates many unnecessary details and is widely cumbersome. Designing suitable highly interactive visual systems will contribute to the network management. In our visualization system, the dynamic interaction is very vital. It can help to solve the large-scale information-overloaded problem and benefit the exploration of network data and the planning and monitoring procedures.

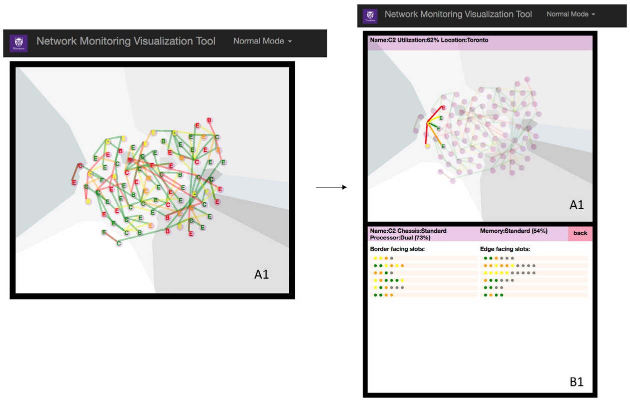
After clicking the update button on the upper right corner of the page in the navigation bar, the simulated data sent from the server will be visualized and displayed in the web browser. The A1 panel, which contains all the main routers in the network, including border routers, core routers, and edge routers, will be displayed in the original view of the visualization system. As demonstrated in Figure 5, when hovering the mouse on a particular node in the network panels, the overall information of this node, including the node name, exact utilization number, and location information, will appear in the purple box on the top of the panel. When the mouse leaves the node, the information will still be shown, and it will only be changed when the mouse is hovering over other nodes. When the mouse hovers over the link, the link information containing the link source, the link target, and link utilization appears in the lower line in the purple box. When the mouse leaves the link, the link information will be disappeared.

In the A1 panel, when clicking the border router or the core routers, the typology of how the selected nodes are connected to other nodes comes into view, as demonstrated in Figure 6. The symbol of the node and its connected nodes are still displayed, while other nodes are blurred, and their symbols are hidden. Only the circles of other nodes are shown to indicate their existence and positions. Only the links that link the clicked node to its connected nodes are vividly shown in the visualization, and the opacity of other links is decreased and turned to gloomy. Thus, the way how the nodes are connected are visualized clearly but also not lose the context. The network administrators or planners can easily catch the connection information of the node they are interested in while still keep the idea of how other nodes are connected. At the same time, the B1 panel will come into view. The inside structure of the selected nodes will be visualized. Users can explore the inside information of the nodes. When clicking the back button on the upper right side of the B1 panel, the B1 panel will disappear, and the A1 panel will return to its original state. No node is selected at this stage, and the whole topology of the border routers, core routers, and edge routers are displayed totally.



Name:E6 Utilization:53% Location:Toronto
Source: C3 Target: E6 Utilization: 20

FIGURE 5. Hovering the nodes or the links.



Name:C2 Utilization:62% Location:Toronto

Name:C2 Chassis:Standard Processor:Dual (73%)
Memory:Standard (54%)

Border facing slots:

Edge facing slots:

FIGURE 6. Clicking one of the core routers in the A1 panel.

As shown in Figure 7-a, if clicking the edge router in the A1 panel, the typology of how the edge router is connected to the core router also be highlighted. Meanwhile, the A2 panel comes into view. When clicking the back button on the upper right side of the A2 panel, the A2 panel will disappear, and the A1 panel will return to its original state. No node is selected, and the whole topology of the border routers, core routers, and edge routers are displayed totally in the A1 panel.

The selected edge router and its linked access routers are visualized in the A2 panel. When clicking the edge

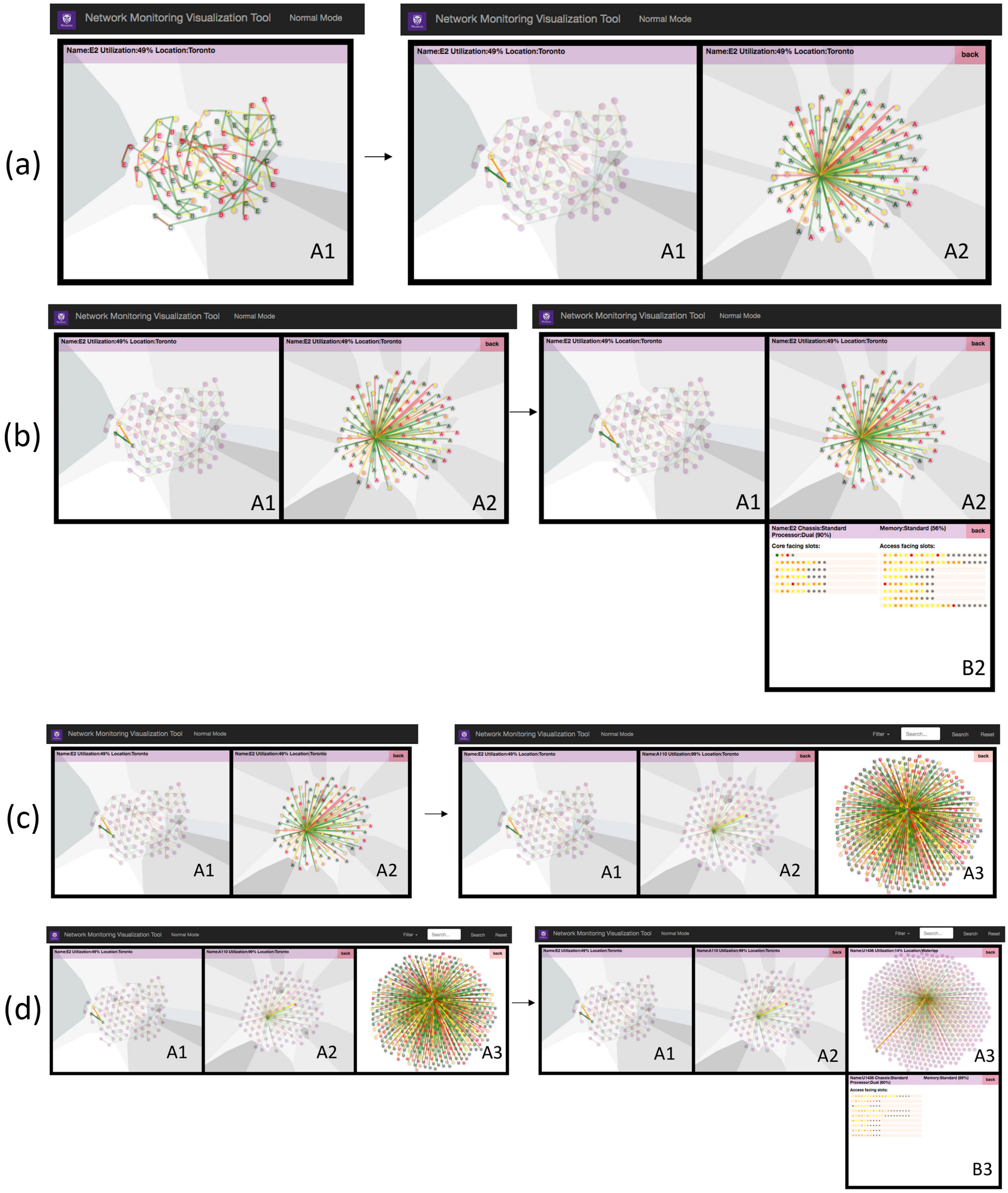


FIGURE 7. **(a). Clicking the edge router in the A1 panel; (b). Clicking the edge router in the A2 panel; (c). Clicking the access router in the A2 panel; (d). Clicking the user in the A3 panel.**

router in the A2 panel, the B2 panel, which indicates the inside structure of the edge router, is shown. When clicking the back button on the upper right side of the B2 panel, the B2 panel will disappear. When clicking the access router in the A2 panel, the topology of how the access router is connected to the edge router is highlighted. Only the symbols of the selected access node and its linked edge node are shown in the A2 view, and the symbols of other nodes are hidden. Meanwhile, the A3 panel, which visualizes the topology of selected access nodes and its linked user nodes, comes into view. The interaction process has been demonstrated in Figure 7-b and Figure 7-c.

When clicking the access node in the A3 view, the B3 panel will be shown. If the back button on the B3 panel is pressed, the B3 panel will be folded. As shown in figure 7-d, if clicking the user node in the A3 view, the user and its linked access node will be highlighted in the A3 panel, and the B3 panel will be shown. When pressing the back button on the B3 panel, the B3 panel will be folded, and the A3 will return to its original state.

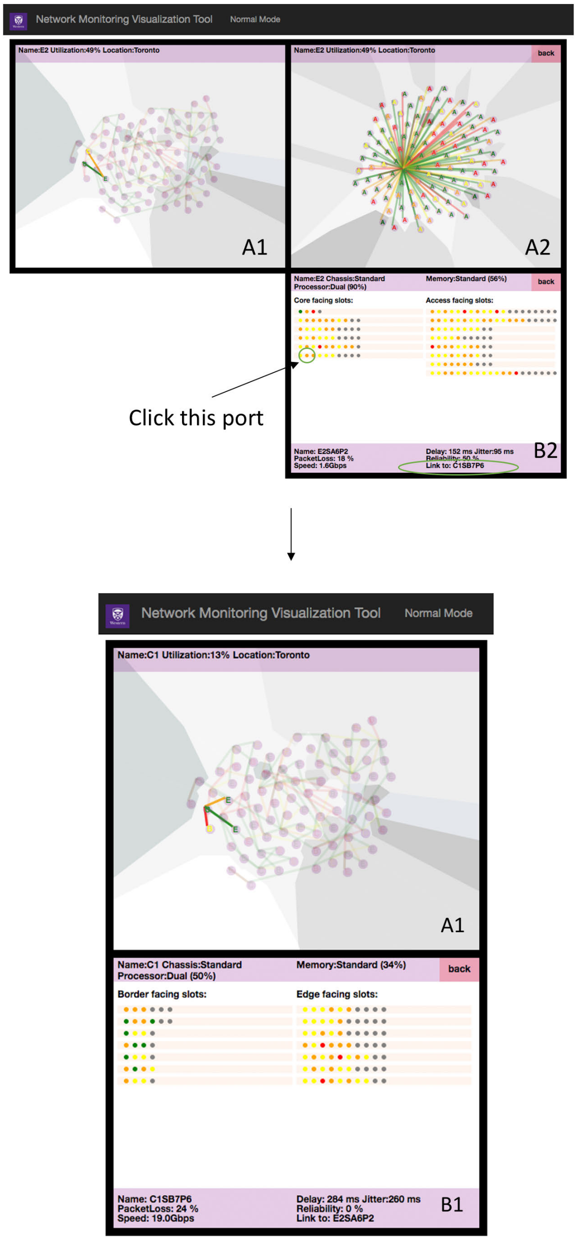
The overall interaction pattern of the node clicking action in the network panel can be summarized as follows. When clicking the node in the network panels, the typology of how the selected node is connected to other nodes comes into view. The symbol of the node and its connected nodes are still displayed, while other nodes are blurred, and their symbols are hidden. Only the circles of other nodes are shown to indicate their existence and positions. Only the links that link the clicked node to its connected nodes are vividly shown in the visualization, and the opacity of other links is decreased and turned to gloomy. Simultaneously, when the node being clicked is in its last panel, the inside panel of this node will be displayed. If the clicked node is not in its last panel, the next panel will be shown, and both the clicked node and the lower hierarchical level of nodes linked to the clicked node will be displayed in the next panel. In the visualization system, the border routers, core routers, and edge routers are visualized in the A1 panel. The selected edge router and its linked access routers are shown in the A2 panel. The A3 panel displays the selected access router and its connected user routers.

In the inside (B1, B2, and B3) panel, when the mouse moves over the ports, the port name, the port it links to, the speed, and the QoS information will be displayed as text in the purple box at the bottom of the panel. The QoS information, including the delay, jitter, packet loss, reliability, will be displayed.

When clicking any of the port, it will turn to show the information of its linked port and the inside information of the router the linked port is in. The inside panel of the current node will be folded, and the inside panel of the node which the linked port is in will be displayed. The visualization will also navigate to show the router's information where the linked port is located, and the network panel will turn to display the connection information of this node. It will only show the information of the current hierarchy of the node where the linked port locates and for example, if the node that the port links to is in the A2 panel, the A3 panel will be disappeared. Also, the node and its linked nodes will be highlighted. It will have the same display as if the node is clicked. As in Figure 8, it can be seen that the ID of the port being hovered is E2SA6P2, and it lies in the line cards in the core facing slot. This port links to the port C1SB7P6, and the port C1SB7P6 belongs to the core router C1. When clicking the port E2SA6P2, the visualization will navigate to show the information of the router C1. The A2 and B2 panel will be hidden. The B1 panel will be displayed to show all the inside information of the core router C1 and also the information of the port C1SB7P6 including its QoS metrics.

E. FILTERING FUNCTION

When the user tends to filter the nodes or the ports according to node utilization, port utilization, port delay, or port packet loss, they could type the number in the form and select the attributes on the drop-down menu. The visualization system will only show the nodes or ports whose selected attribute is higher than the number. After filtering the nodes, the users can also select the port attribute on the drop-down menu and input the number. The visualization system can display both part of the nodes and part of the ports whose utilization, delay or packet loss is higher than the input number. The high utilization, delay, or packet loss indicates that there may be some anomalous changes or activities, and it will lead to degraded services and utilization. Therefore, showing the routers or the ports that may have potential problems is beneficial for troubleshooting and performance monitoring in network management and network planning. The views



Name:E2 Utilization:49% Location:Toronto

Name:E2 Chassis:Standard
Processor:Dual (90%)
Memory:Standard (56%)

Core facing slots:
Access facing slots:

Name: E2SA6P2
PacketLoss: 18 %
Speed: 1.6Gbps
Delay: 152 ms Jitter:95 ms
Reliability: 50 %
Link to: C1SB7P6

Name:C1 Utilization:13% Location:Toronto

Name:C1 Chassis:Standard
Processor:Dual (50%)
Memory:Standard (34%)

Border facing slots:
Edge facing slots:

Name: C1SB7P6
PacketLoss: 24 %
Speed: 19.0Gbps
Delay: 284 ms Jitter:260 ms
Reliability: 0 %
Link to: E2SA6P2

FIGURE 8. When clicking the port, it will navigate fo show the inside data of the router where the linked port located and the information of the linked port.

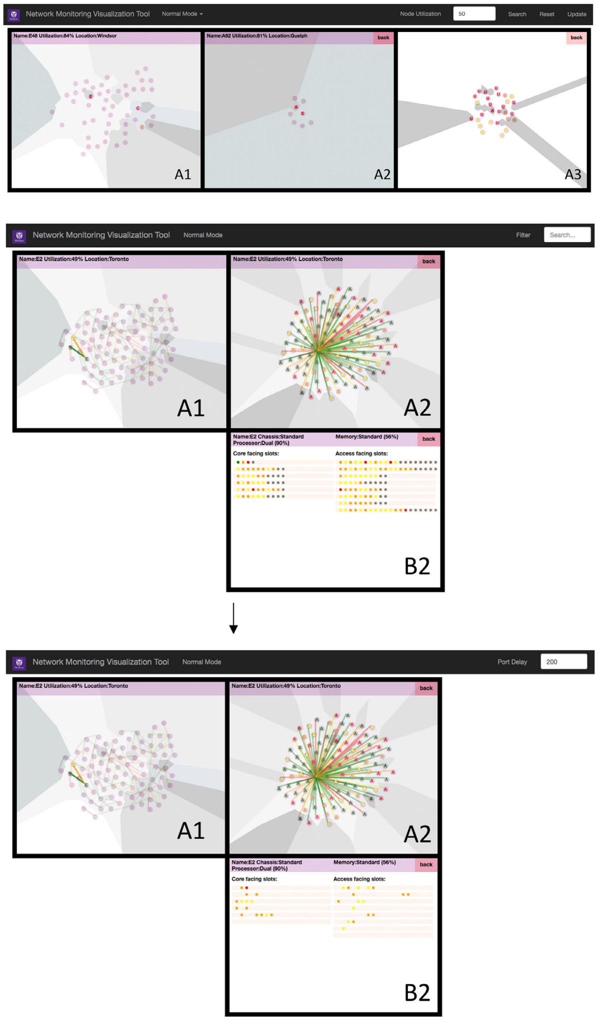


FIGURE 9. **(a). Filtering the routers according to the router utilization (up); (b). Filtering the ports according to the port delay (down).**

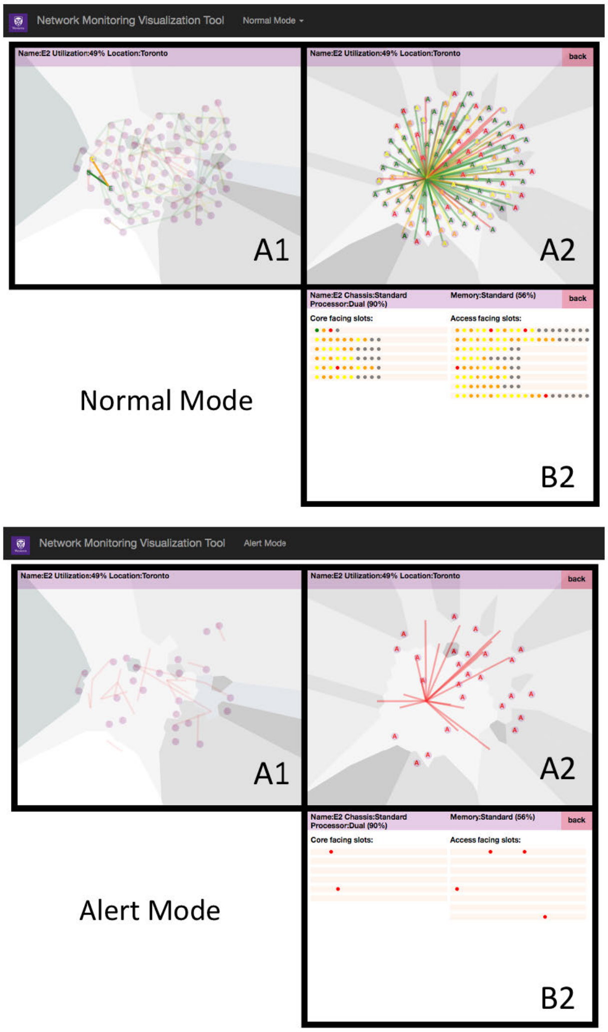


FIGURE 10. **The comparison between the normal mode and the alert model.**

after filtering the routers according to their utilizations are demonstrated in Figure 9-a, and Figure 9-b illustrates the change in the views when filtering the ports according to the port delay.

F. ALERT MODE

Besides the normal mode described above, the visualization system also provides an alert mode for network administrators to directly catch the anomaly so they could handle it efficiently. The comparison between the normal mode view and the alert mode view is demonstrated in Figure 10. When choosing the alert mode in the drop-down menu on the top bar in the system, the visualization will only display the red nodes, links and ports. The red color means the utilization is higher than 80%. In this way, the workload of monitoring could be reduced, and the network administrators could quickly identify the meaningful anomalous activities.

V. CASE STUDY

Effectively visualizing large-scale networks has been considered difficult with traditional methods because the density of the link is high, and the relationship between nodes is complex. Given the limited screen space, it is essential to explore how to present ultra-large-scale network data efficiently to assist Internet Service Provider's (ISP) network planning and management activities. To overcome the limitation of the node-link layout in a large-scale network, many previous works have explored this problem and proposed the following methods: adopting parameter focusing, zooming techniques, 3D layout, and novel graph modeling. However, there still exist some problems with these methods. Some visualization systems may lose the context or be confusing to navigate. Others may not be able to contain enough details or visualize the ultra-large-scale network data efficiently.

Configuration management is one of the essential areas for network management. It allows a network operator to track which devices are on the managed network and the hardware and software configurations of these devices [59]. Also, providing Quality of Service (QoS) guarantee is an essential requirement for network performance management [12]. This network monitoring visualization system intends to help network administrators efficiently detect possible degradation and easily figure out the possible anomalous devices so that it will be easy to tune the network resources accordingly. Also, it should benefit the network planners in conducting their network health analysis and aid in capacity planning since the network congestion points can be easily identified.

According to the requirements, several direct case studies have been proposed to illustrate and examine this visualization system:

A). Can the network administrators/planners efficiently detect the anomalous routers, links, or ports?

B). Can the network administrators/planners easily identify the node and its linked node?

C). Can the network administrators/planners easily figure out the configuration of the routers?

D). Can the network administrators/planners monitor the QoS and detect possible QoS degradation?

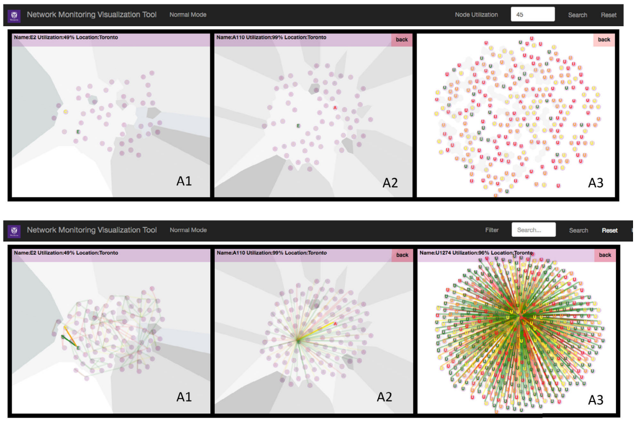
E). Can the network administrators identify the connection between each port? Can the network administrators/planners navigate through the network in the level of ports?

F). Can the network administrators/planners interact with the network visualization system and filter the data to better monitor the network and derive the filtered data report for future purposes?

A: In the normal mode, through the color of each node, link, and port, it is easy to figure out which range their utilization is in. When the mouse moves over the nodes or links, their exact utilization number will be displayed in the window on the top of the panel. The alert mode will only display the network elements with extremely high utilization, which means all the elements displayed on the screen need particular attention. Instead of being driven by request and query, the alert mode provides more direct ways to alert the network administrators. Network administrators can interact with these elements in the same way as in the normal mode. Network administrators can easily convert between these two modes without losing the exploration stage and increasing the workload. In this way, the anomalous nodes, links, and ports can be easily detected.

B: When clicking one of the nodes, only the symbols of the selected router and its linked routers are shown, and the symbols of other routers will be hidden. In this way, the relationship between the nodes can easily be identified and analyzed. In addition, the three network panels make it clear to identify the hierarchy of each connection and the number of hops between two nodes.

C: In the network panel, when the mouse is hovering around the router, its ID, its utilization, and its location will be displayed as text in the window at the top of the panel. The background color of the area where the router is placed indicates the router's location as well. When the inside panel of the selected router is displayed, it is easy to identify its facing slot(s) and its line cards. It is easy to identify the number of line cards in each slot in the router and the ports' condition located in each card. Also, the concrete information of the selected router will be shown on the top of the inside panel, which includes the name of the router, the chassis type, the memory type, the memory's utilization, the processor type, and the processors' utilization.



Node Utilization 45

Name:E2 Utilization:49% Location:Toronto

Name:A110 Utilization:99% Location:Toronto

Filter Search...

Name:E2 Utilization:49% Location:Toronto

Name:A110 Utilization:99% Location:Toronto

Name:U1274 Utilization:96% Location:Toronto

FIGURE 11. Filter the routers with specific utilization range (Up); The original view without applying the filtering function (Down).

D: In the inside panel, when the mouse moves over the ports, the specific QoS information of the port will be shown as text in the window at the bottom of the panel. The network administrators can also filter the ports according to their port utilization, port delay, or port packet loss. Only the ports whose port utilization, port delay, or port packet loss is beyond the standard will be displayed. Users can interact with the visualization and explore the network with these ports. In this way, it is very efficient to detect possible QoS degradation, conduct health analysis, and still can obtain enough information of the network.

E: In the inside panel, when clicking the port, it will navigate to the port it links to. The inside panel of the current router will be folded, and the inside panel of the router where the linked port is located will be shown. The information of the linked port, including the speed and QoS metrics, will be displayed as text at the bottom of the inside panel. Meanwhile, the router in the network panel will be highlighted. If some port has a degraded service, it is very convenient to identify and locate which port it links to and check the condition of the linked port and its routers. It is beneficial for the network administrators or planners to identify the anomalous element and efficiently check the condition of elements that may be affected.

F: As mentioned in the D case, the visualization system enables users to filter the port to better detect possible QoS degradation. Besides this, the nodes can also be filtered according to the router utilization. As presented in Figure 11, only the suspect routers are displayed in the panel. In addition, the data information of the filtered ports or the filtered routers will be stored in the additional data file as the performance report for future use.

VI. CONCLUSION AND FUTURE WORK

This paper explores how to visualize the large-scale network data and provide enough low-level details and thus enables the network planners or administrators to plan and monitor the next-generation communication network efficiently. Our system introduces a way of elegantly visualizing the topology of a large-scale computer network and visualizes the relevant information concerning it, including the router configuration and port level QoS metrics. The visualization system combines the design strategies of progressive disclosure and multiple panels, and it divides the routers according to its hierarchy and visualizes them in different panels with the semantic zooming and brushing interaction techniques for users to monitor and explore the network.

Representing network information in detail has often been considered cumbersome due to inefficient visual network topology abstraction and overloaded layout. Compared with the previous works that adopt parameter focusing, zooming techniques, 3D layout, or novel graph modeling methods, this system can clearly visualize and display the information of the inside configuration of the routers and the port level QoS metrics, with the designed multiple panels layout. Also, network administrators and network planners will not lose the context of the connection and condition information during the exploration. It is easy to navigate through both the router-level connection and port-level connection. The system could improve users' response time and speed up identifying the trouble to better solve anomaly problems and conduct health analysis. Additionally, the system provides the data filtering feature for the users to better plan and monitor the communication network. The different modes, including the normal mode and alert mode, can satisfy the diverse needs and benefit the monitoring process. The visualization system proposed in this paper is real-time, and it improves diagnoses and supports timely response and decision making.

In the future, the system could involve real-world large-scale data collection, salient features extraction, and data analysis to better structure the real-word data for visualization. Additionally, more options may be provided for users to choose whether to update the visualization automatically or manually. We also plan to extend the system with more advanced features and techniques, such as combining some machine learning techniques to predict the anomaly and the fluctuation of the QoS, and cluster the routers, the links, and the nodes. The router nodes could be divided according to these clusters and visualized in different panels, besides according to the hierarchy of the routers. In addition, we aim to provide a timeline with long-term historical data over the same view to aid in capacity planning, and analyze the QoS metrics information to provide some summary statistic charts. In this way, overloaded elements of the network could be easily identified and analyzed. Furthermore, the traffic flow monitoring and packet-level capture can be visualized upon this visualization system in the future, and some animation of events could be provided to recognize the unusual behavior and benefit the resource allocation and planning.

REFERENCES

[1] L. Xiao, J. Gerth, and P. Hanrahan, "Enhancing visual analysis of network traffic using a knowledge representation," in *Proc. IEEE Symp. Vis. Analytics Technol.*, Oct. 2006, pp. 107–114.

[2] W. Dargie and C. Poellabauer, *Fundamentals of Wireless Sensor Networks*. Hoboken, NJ, USA: Wiley, 2010.

[3] V. T. Guimaraes, C. M. D. S. Freitas, R. Sadre, L. M. R. Tarouco, and L. Z. Granville, "A survey on information visualization for network and service management," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 1, pp. 285–323, 1st Quart., 2016.

[4] B. Li, J. Springer, G. Bebis, and M. H. Gunes, "A survey of network flow applications," *J. Netw. Comput. Appl.*, vol. 36, no. 2, pp. 567–581, Mar. 2013.

[5] N. Tateishi, M. Tahara, N. Tanji, and H. Seshake, "Method for visualizing information from large-scale carrier networks," in *Proc. Netw. Oper. Manage. Symp.*, Sep. 2013, pp. 1–6.

[6] Q. Liao, A. Blaich, D. VanBruggen, and A. Striegel, "Managing networks through context: Graph visualization and exploration," *Comput. Netw.*, vol. 54, no. 16, pp. 2809–2824, Nov. 2010.

[7] D. Lalanne, E. Bertini, P. Hertzog, and P. Bados, *Visual Analysis of Corporate Network Intelligence, Abstracting and Reasoning on Yesterdays for Acting Today*. Berlin, Germany: Springer, 2007.

[8] S. K. Card, J. D. Mackinlay, and B. Shneiderman, *Readings in Information Visualization: Using Vision To Think*. San Mateo, CA, USA: Morgan Kaufmann, 1999.

[9] T. Zhang, X. Wang, Z. Li, F. Guo, Y. Ma, and W. Chen, "A survey of network anomaly visualization," *Sci. China Inf. Sci.*, vol. 60, no. 12, pp. 1–17, Dec. 2017.

[10] H. Wang, "From a mess to graphic maps: Visualization of large-scale heterogeneous networks," in *Proc. 2nd Int. Conf. Comput. Modeling Simulation*, Jan. 2010, pp. 531–535.

[11] L. Atzori, A. Iera, and G. Morabito, "The Internet of Things: A survey," *Comput. Netw.*, vol. 54, no. 15, pp. 2787–2805, Oct. 2010.

[12] C.-K. Tham, Y. Jiang, and C.-C. Ko, "Monitoring QoS distribution in multimedia networks," *Int. J. Netw. Manage.*, vol. 10, no. 2, pp. 75–90, Mar. 2000.

[13] Y. Wu, P. A. Chou, Q. Zhang, K. Jain, W. Zhu, and S.-Y. Kung, "Network planning in wireless ad hoc networks: A cross-layer approach," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 1, pp. 136–150, Jan. 2005.

[14] R. A. Becker, S. G. Eick, E. O. Miller, and A. R. Wilks, "Dynamic graphics for network visualization," in *Proc. 1st IEEE Conf. Vis., Visualizat.*, Oct. 1990, pp. 93–96.

[15] R. Hofstede and T. Fioreze, "SURFmap: A network monitoring tool based on the Google maps API," in *Proc. IFIP/IEEE Int. Symp. Integr. Netw. Manage.*, Jun. 2009, pp. 676–690.

[16] A. Inoue, Y. Takahashi, and A. Koyama, "MANET viewer III: 3D visualization system for mobile ad hoc networks," in *Proc. 16th Int. Conf. Netw.-Based Inf. Syst.*, Sep. 2013, pp. 178–185.

[17] S. C. Au, C. Leckie, A. Parhar, and G. Wong, "Efficient visualization of large routing topologies," *Int. J. Netw. Manage.*, vol. 14, no. 2, pp. 105–118, Mar. 2004.

[18] M. F. Franco, R. L. Dos Santos, A. Schaeffer-Filho, and L. Z. Granville, "VISION - interactive and selective visualization for management of NFV-enabled networks," in *Proc. IEEE 30th Int. Conf. Adv. Inf. Netw. Appl. (AINA)*, Mar. 2016, pp. 274–281.

[19] B. Cheswick, H. Burch, and S. Branigan, "Mapping and visualizing the Internet," in *Proc. USENIX Annu. Tech. Conf., Gen. Track*. Princeton, NJ, USA: Citeseer, 2000, pp. 1–12.

[20] T. Qiu, Z. Ge, D. Pei, J. Wang, and J. Xu, "What happened in my network: Mining network events from router syslogs," in *Proc. 10th Annu. Conf. Internet Meas. IMC*, 2010, pp. 472–484.

[21] J. Abello, S. G. Kobourov, and R. Yusufov, "Visualizing large graphs with compound-fisheye views and treemaps," in *Proc. Int. Symp. Graph Drawing*. New York, NY, USA: Springer, 2004, pp. 431–441.

[22] E. R. Gansner, Y. Koren, and S. C. North, "Topological fisheye views for visualizing large graphs," *IEEE Trans. Vis. Comput. Graphics*, vol. 11, no. 4, pp. 457–468, Jul. 2005.

[23] F. Mansmann, F. Fischer, D. A. Keim, and S. C. North, "Visual support for analyzing network traffic and intrusion detection events using TreeMap and graph representations," in *Proc. Symp. Comput. Hum. Interact. Manage. Inf. Technol. (CHiMiT)*, 2009, pp. 19–28.

[24] Z. Kan, C. Hu, Z. Wang, G. Wang, and X. Huang, "NetVis: A network security management visualization tool based on treemap," in *Proc. 2nd Int. Conf. Adv. Comput. Control*, Mar. 2010, pp. 18–21.

[25] F. Fischer, F. Mansmann, D. A. Keim, S. Pietzko, and M. Waldvogel, "Large-scale network monitoring for visual analysis of attacks," in *Proc. Int. Workshop Visualizat. Comput. Secur.* New York, NY, USA: Springer, 2008, pp. 111–118.

[26] L. Williams, R. Lippmann, and K. Ingols, "An interactive attack graph cascade and reachability display," in *Proc. VizSEC*. New York, NY, USA: Springer, 2008, pp. 221–236.

[27] L. Harrison, M. Iannacone, E. Downing, and J. R. Goodall, "NV: Nessus vulnerability visualization for the Web categories and subject descriptors," in *Proc. 9th Int. Symp. Visualizat. Cyber Secur.*, 2012, pp. 25–32.

[28] W. Xu, M. Shehab, and G.-J. Ahn, "Visualization based policy analysis: Case study in SELinux," in *Proc. 13th ACM Symp. Access Control Models Technol. SACMAT*, 2008, pp. 165–174.

[29] A. Lu, W. Wang, A. Dnyate, and X. Hu, "Sybil attack detection through global topology pattern visualization," *Inf. Visualizat.*, vol. 10, no. 1, pp. 32–46, Jan. 2011.

[30] M. Figueredo Franco, R. L. D. Santos, R. Cava, E. J. Scheid, R. J. Pfitscher, C. Dal Sasso Freitas, and L. Zambenedetti Granville, "Interactive visualizations for planning and strategic business decisions in NFV-enabled networks," in *Proc. IEEE 31st Int. Conf. Adv. Inf. Netw. Appl. (AINA)*, Mar. 2017, pp. 492–499.

[31] Y. Kumata and A. Koyama, "Mesh net viewer: A visualization system for wireless mesh networks," in *Proc. 8th Int. Conf. Broadband Wireless Comput., Commun. Appl.*, Oct. 2013, pp. 80–87.

[32] J. R. Goodall, W. G. Lutters, P. Rheingans, and A. Komlodi, "Preserving the big picture: Visual network traffic analysis with TNV," in *Proc. IEEE Workshop Visualizat. Comput. Secur. (VizSEC)*, Oct. 2005, pp. 47–54.

[33] D. M. Best, S. Bohn, D. Love, A. Wynne, and W. A. Pike, "Real-time visualization of network behaviors for situational awareness," in *Proc. 7th Int. Symp. Visualizat. Cyber Secur. VizSec*, 2010, pp. 79–90.

[34] A. Gubin, W. Yurcik, and L. Brumbaugh, "Network management visualization with PingTV," in *Proc. 26th Annu. IEEE Conf. Local Comput. Netw. LCN*, Feb. 2001, p. 62.

[35] H. Choi, H. Lee, and H. Kim, "Fast detection and visualization of network attacks on parallel coordinates," *Comput. Secur.*, vol. 28, no. 5, pp. 276–288, Jul. 2009.

[36] S. Tricaud, K. Nance, and P. Saade, "Visualizing network activity using parallel coordinates," in *Proc. 44th Hawaii Int. Conf. Syst. Sci.*, Jan. 2011, pp. 1–8.

[37] V. T. Guimaraes, O. M. C. Rendon, G. L. dos Santos, G. da Cunha Rodrigues, C. M. Dal Sasso Freitas, L. M. Rockenbach Tarouco, and L. Z. Granville, "A reuse-based approach to promote the adoption of visualizations for network management tasks," in *Proc. IEEE 31st Int. Conf. Adv. Inf. Netw. Appl. (AINA)*, Mar. 2017, pp. 712–719.

[38] A. Douitsis and D. Kalogeras, "Interactive network management visualization with SVG and AJAX.," in *Proc. 20th Conf. Syst. Admin.*, 2008, p. 19.

[39] S. T. Eick, "Aspects of network visualization," *IEEE Comput. Graph. Appl.*, vol. 16, no. 2, pp. 69–72, Mar. 1996.

[40] *Les Misérables Matrix*. Accessed: Oct. 20, 2019. [Online]. Available: https://bost.ocks.org/mike/miserables/

[41] E. R. Gansner, S. C. North, and F. Park, "Large-scale network visualization," *SIGGRAPH Newslett.*, vol. 33, no. 3, pp. 13–15, 1999.

[42] G. Parulkar, D. Schmidt, E. Kraemer, J. Turner, and A. Kantawala, "An architecture for monitoring, visualization, and control of gigabit networks," *IEEE Netw.*, vol. 11, no. 5, pp. 34–43, Sep. 1997.

[43] Y. Tsutsui, Y. Kitaura, K. Kikuchi, T. Ohta, and Y. Kakuda, "Development of a real-time system for visualizing network topology and packet flow in MANET field experiments," in *Proc. 10th Int. Conf. Mobile Ad-Hoc Sensor Netw.*, Dec. 2014, pp. 151–157.

[44] H. Fuji, S. Nakai, H. Matoba, and H. Takano, "Real-time bifocal network-visualization," in *Proc. NOMS IEEE Netw. Oper. Manage. Symp.*, Feb. 2002, pp. 867–876.

[45] *WebSocket*. Accessed: Feb. 9, 2020. [Online]. Available: https://en.wikipedia.org/wiki/WebSocket

[46] Tornadoweb.org. *Tornado Web Server–Tornado 6.0.4 Documentation*. Accessed: Feb. 9, 2020. [Online]. Available: https://www.tornadoweb.org/en/stable/

[47] L. F. de Camargo, A. Moraes, D. R. Dias, and J. R. Brega, "Information visualization applied to computer network security," in *Proc. Int. Conf. Comput. Sci. Appl.* New York, NY, USA: Springer, 2020, pp. 44–59.

[48] C. Academy. *Hierarchical Network Design Overview*. Accessed: Oct. 20, 2019. [Online]. Available: https://www.ciscopress.com/articles/article.asp?p=2202410&seqNum=4

[49] *Wsdream*. Accessed: Dec. 15, 2019. [Online]. Available: https://github.com/wsdream/wsdream-datasetv

[50] *QWS Dataset*. Accessed: Dec. 15, 2019. [Online]. Available: https://qwsdata.github.io/

[51] *Simulated Cloud Service QoS Dataset*. Accessed: Dec. 15, 2019. [Online]. Available: https://data.mendeley.com/datasets/5vffs75j85/1

[52] N. Nielsen. *Progressive Disclosure*. Accessed: Oct. 20, 2019. [Online]. Available: https://www.nngroup.com/articles/progressive-disclosure/

[53] K. Sedig, P. Parsons, H.-N. Liang, and J. Morey, "Supporting sensemaking of complex objects with visualizations: Visibility and complementarity of interactions," *Informatics*, vol. 3, no. 4, p. 20, Oct. 2016.

[54] R. Spence, *Information Visualization*. New York, NY, USA: Springer, 2001.

[55] *Verlet Integration*. Accessed: Sep. 7, 2019. [Online]. Available: https://resources.saylor.org/wwwresources/archived/site/wp-content/uplo%ads/2011/06/MA221-6.1.pdf

[56] *d3/d3-force*. Accessed: Sep. 7, 2019. [Online]. Available: https://github.com/d3/d3-force

[57] F. P. Preparata and M. I. Shamos, *Computational Geometry: An Introduction*. New York, NY, USA: Springer, 2012.

[58] A. Telea and J. J. Van Wijk, "Visualization of generalized Voronoi diagrams," in *Data Visualization*. New York, NY, USA: Springer, 2001, pp. 165–174.

[59] J. F. Kurose and K. W. Ross, *Computer Networking A Top-Down Approach*. London, U.K.: Pearson, 2017.

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