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Network Visualization Design using Prefuse Visualization Framework

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Network Visualization Design using Prefuse Visualization Toolkit

THESIS

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Abstract

Visualization of network simulation events or network visualization is an effective and low cost method to evaluate the health and status of a network and analyze network designs, protocols, and network algorithms. This research designed and developed a network event visualization framework using an open source general visualization toolkit. This research achieved three major milestones during the development of this framework: A robust network simulator trace file parser, multiple network visualization layouts–including user-defined layouts, and precise visualization timing controls and integrated display of network statistics. The parser architecture is extensible to allow customization of simulator trace formats that are accepted by the visualization framework. This design makes the framework capable of accepting trace files from different network simulators and provides one common visualization testbed to study network scenarios run on different simulators. Multiple network visualization layouts are made possible using the `prefuse` visualization toolkit `Layout` class which provides many different visualization layouts and is easily extensible to create new `Layout` subclasses. Finally, precise timing controls give users better control for quicker navigation to specific network events at any time. The toolkit design is readily extensible allowing developers to easily expand the framework to meet research-specific visualization goals.

Acknowledgements

I would first like to thank Josh Abernathy from Cedarville college for his contributions towards building the network visualization framework and his extensive knowledge of `prefuse`. Also my wife for her help and support and my lab mates who kept me sane during the long hours of writing and coding. Finally, I would like to acknowledge the great effort of my thesis advisor Lt Col Kurkowski who helped me organize my writing and kept me believing all things were possible.

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I. Introduction

Throughout history, military operations have relied heavily on an accurate picture of the battlespace. On land or at sea, early military operations used maps to visualize ship locations, troop positions, and even different characteristics of the land. Commanders used the maps to plan and carry out strategic strikes against enemy positions. However, as time passed and technology improved so did the tools used to create a picture of the battlespace. Sonar significantly improved the naval battlespace picture by using sound waves to locate submarines buried deep in the sea, invisible to the human eye. As military operations took to the skies, it was necessary to provide an aerial battlespace picture. Technology aided this endeavor by combining radar technology with a cathode-ray tube display to produce the first real-time picture of airspace–the Plan Position Indicator [22]. This device oriented the radar signal source at the center of the display with an extended line rotating around the signal source in a sweeping motion. The radar display sweep was synchronized with the turning of the physical radar scan. Aircraft detected by the physical radar scan appeared as lighted dots on the display and their positions updated during each sweep. These early tools filled the inherent need to see the battlespace picture visually and motivated future battlespace visualization enhancements.

Military technology today has advanced beyond the early capabilities of maps, sonar and radar. Today, commanders have battlespace pictures captured and transferred from around the world using different combinations of radar, sonar, GPS, and satellite image systems. These tracking technologies are combined to produce a battlespace visualization for land, sea, and air. However, bringing together a com-

prehensive visualization requires large and complex computer communication networks. Further increasing the demand for large communication networks, newly developed Unmanned Aerial Vehicles (UAVs) and Unmanned Combat Aerial Vehicles (UCAVs) require networks with high capacity communication uplinks to fulfill their missions [38]. Because UAVs/UCAVs rely heavily on computer communication networks to be successful, there is a greater requirement to monitor, design, and plan these networks. Additionally, reliance on communication networks will only increase as UAV/UCAV technology continues to expand and advance as the US and allies develop new technologies like the Pegasus, X-45, Neuron and Phoenix [11].

Military networks continue to grow into a bigger part of the way we conduct war. Future military in-theater communication will rely on mobile routers imbedded in a variety of different places from devices carried by soldiers, to manned and unmanned land, sea, and air based vehicles. Due to the mobile nature of these future networks, connections between different nodes will sporadically be up and down. How networks adapt to these changes is critical to overall network efficiency. Vital to guaranteeing efficient network usage and effective command and control of military assets is a central view of network events and activities.

Network visualization is crucial to understanding and effectively managing network resources required during military land, sea, and air operations. Building a network visualization framework capable of handling the large and complex computer, and communication networks found today starts with a framework that can handle simple network events. The easiest way to generate these simple network events is to use the visualization framework to visualize network events from a network simulator. However, many commonly used network simulators today already have accompanying network visualization frameworks. Some of these visualization frameworks include: Network Animator (Nam), interactive Network Simulator 2 protocol and environment confirmation tool (iNSpect), Georgia Tech Network Simulator (GTNets) and the Optimized Network Evaluation Tools (OPNET). Although these visualizations illustrate network events for their accompanying network simulator they motivate the develop-

ment of a new more universal visualization framework that provide better network analysis tools. This research presents the design, implementation, and testing of a new visualization framework to improve network visualization of wired, wireless, and multi-hop wireless network scenarios and provide network analysis tools.

The new network visualization framework presented in this research extends the widely used ***prefuse*** visualization toolkit [16]. A brief overview of different toolkits: Guess, Osprey, Piccolo, Qt, and ***prefuse*** motivated the selection of ***prefuse*** as the best suited for this framework. The new framework design provides trace file parsing for trace files from Network Simulator-2 (NS-2). However, the framework includes a file parser base class which users can easily extend or modify to create a trace file parser for other network traces.

This research provides three major contributions with the new framework. First, a trace file parser for NS-2 traces that is easily extensible to include traces in other formats. Second, a multi-objective network topology visualization layout that can also be easily extended to highlight specific user network behavior interests. Finally, an analysis-based user interface to control the visualization. This research also tested the network visualization framework functionality by comparing visualization output to Nam.

The visualization framework provides: an easily extensible network trace parser for accepting multiple trace file formats, multiple extensible network topology layouts, and an analysis-based user interface. Future work will build upon the parser architecture to handle different network trace formats from real-world networks. Additionally, the flexible layout architecture will allow developers to customize the visualization to commander preferences. The framework provides network event visualization with the flexibility needed to visualize today's large and complex networks.

II. Network Simulation and Visualization

Researchers use network simulator software suites to simulate network events. To perform these simulations, users first choose a network simulator such as Network Simulator-2 (NS-2), Optimized Network Evaluation Tools (OPNET), Georgia Tech Network Simulator (GTNetS) Omnet++, or GloMoSim [5]. Second, they create a network topology inside the simulator using the provided simulator interface. Finally, they create a scenario for the simulator to run on the network topology. After execution, the simulator provides a statistical report detailing how the network performed during scenario execution. The simulator report is often lengthy, and locating the pertinent information in the report can be difficult. Additionally, reports only contain network performance statistics. It is very difficult to understand how the network is working and evaluate network protocols without actually watching packet routing. To eliminate the effort of finding information in reports and to facilitate better network packet routing observation, researchers have developed software suites to visualize network events run on a network simulator.

Visualization of network events is a crucial part of testing new network designs and analyzing network efficiency. Network architects can design a network inside a network simulator and then visualize how the network will perform under specific scenarios. A network visualization quickly reveals sources of network inefficiencies such as: queuing delays, dropped packets, network congestion, and insufficient bandwidth. Additionally, network visualizations provide protocol developers a powerful method to quickly evaluate their protocols by visually analyzing network packet traffic. The important role of network visualizations in designing networks and analyzing network traffic warrants an evaluation of current network visualization suites

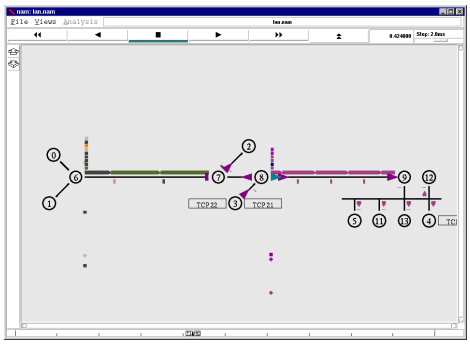
Network visualization suites include both separate programs designed to work with a simulator and programs integrated into the network simulators. Four of these visualization suites are: Nam, iNSpect, GTNetS, and OPNET. Nam visualizes network events (packet flow, links, and queuing) on wired network topologies. The iNSpect program visualizes wireless-specific network events (packet hops, wireless node

links, and packet delivery success) [26]. Both Nam and iNSpect are network visualization frameworks for NS-2. GTNets is a network simulator integrated with packet level visualization and limited wireless support. OPNET shows network events for both wired and wireless networks, but is a proprietary software platform for the OPNET simulator. Section 2.1 explores Nam, iNSpect, GTNetS, and OPNET in greater detail.

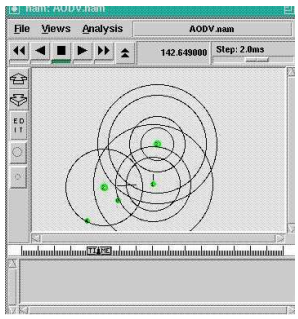
The existence of several different visualizations and network simulators built from the ground up for each simulator raises the questions: Can a single network visualization framework be created to effectively visualize both wired and wireless network simulator scenarios? What about network scenarios created in different simulators (NS-2, OPNET, etc.)? This framework combines network simulator trace data with a well-established visualization toolkit to create an efficient and robust framework. This new visualization framework accurately animates network events contained in a simulation trace file. A major decision during the design of the visualization frameowkr was selecting an existing visualization toolkit that encouraged code reuse with loose coupling between the toolkit and the framework using it [13]. The analysis found in section 2.2 further discusses visualization toolkit selection.

2.1 Network Simulator Visualizations

2.1.1 Nam. When NS-2 executes a network scenario it produces a trace file, containing network events that occurred during the scenario. Nam, a separate program from NS-2, uses the NS-2 trace file to animate a visual representation of the network events that occurred during the scenario. Combining NS-2 with Nam users can define specific network scenarios and network events, run the scenarios in NS-2, and then see the network events visualized as they are re-created in the Nam window (see Figure 2.1(a)). Nam provides packet-level animation, protocol graphs, traditional time-event plots of protocol actions and scenario editing capabilities to NS-2 [7].



(a) Wired Network Nam Visualization showing packet traffic, queued packets, and dropped packets



(b) Wireless Network Nam Visualization showing broadcast rings

Figure 2.1: Nam Visualization

Originally built to support wired network visualization Nam has limited wireless network animation capabilities. Nam visualizes wireless traffic as broadcast rings moving outward originating from the center of wireless nodes (see Figure 2.1(b)). Nam allows user interaction with the simulator through the scenario input facility, but is limited to setting up network scenarios. The scenario input facility uses traditional drawing approaches to add nodes, links, and protocol agents [7]. This user interaction is limited to activities prior to scenario execution; Nam does not allow user interaction while a scenario is running and does not facilitate two-way communication between the visualization and the simulator.

Nam provides a good baseline for wired network event animation. Packet routing, queueing, and dropping are all visible and easily recognized. Nam visualization of these network events makes network and protocol evaluation possible. However wireless network event visualization shortfalls in Nam have opened the door for new visualization frameworks that provided better wireless network event visualization.

2.1.2 iNSpect. The iNSpect program, a wireless network visualization tool used with NS-2, tackles the wireless network visualization shortfalls left by NAM [26]. The tool shows various actions unique to wireless networks including: node movement, packet routing, node broadcast radii, and geometric shape overlays to repre-

sent physical boundaries. The iNSpect program accurately visualizes how packets are routed through a wireless network by generating arrows to indicate packets moving from one node to another and color coding nodes to indicate source (blue), destination (red or green), and path nodes (yellow) (see Figure 2.2).

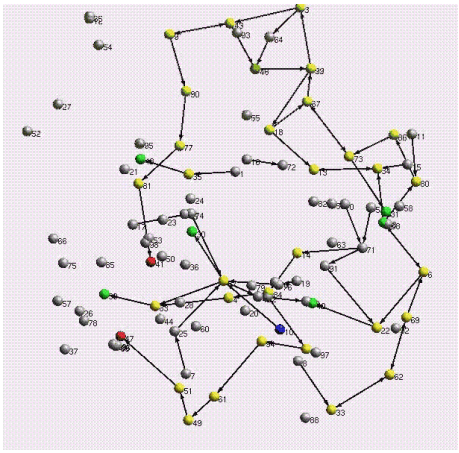


Figure 2.2: iNSpect visualization highlighting packet routing nodes: source (blue), intermediate (yellow), destination (red or green)

The iNSpect program is a definite improvement in wireless network event visualization over Nam. The program uses arrows and color coded nodes to highlight packet routes which allows users to evaluate wireless network events and protocols. However, illustrating packet transmission from one node to another with arrows is less intuitive then simply animating packet movement between nodes. The iNSpect program's packet animation could be improved by showing packet traffic as it is shown in wired network event animation, with small rectangles moving from node to node. The program also requires NS-2 to produce larger trace files (almost a factor of 2) than are required for Nam. A final drawback to the iNSpect program is that only wireless network traffic is visualized. The iNSpect program's visualization of wireless packet routing is a powerful tool, however, a framework that combines wireless network traffic with intuitive network packet animation would be better.

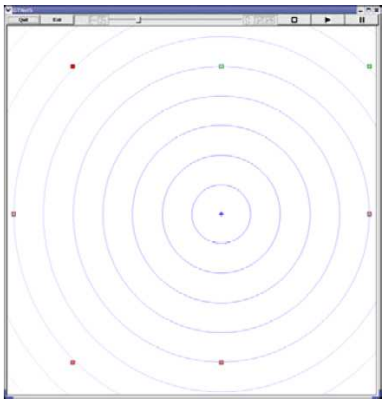


Figure 2.3: GTNets visualizer showing wireless broadcast rings [39]

2.1.3 GTNets. Unlike Nam and iNSpect GTNetS combines a full-featured network simulation environment with graphical viewing of the simulation topology . The network simulation suite shows the network topology along with network traffic (see Figure 2.3). GTNets also provides fine-grain control mechanisms whereby a network trace file is created [14]. The source code for GTNets is freely available to all users of the simulator / network visualization. By modifying the C++ code developers can tailor the simulator to meet their own needs. However, this give GTNets little advantage over NS-2 which also makes source code freely available. Similar statistical reports are available in GTNetS as those found in NS-2 [32]. The major advantage of GTNetS over NS-2 is the ability to support large numbers of nodes and packet traffic with only moderate increase in simulation time. Figure 2.4 shows GTNets ability to handle large network topologies. Data contained in Figure 2.4 was obtained from loggin a Department of Defense computer network while adding multimedia and encrypted traffic [27]. GTNets creates a network simulation environment with both a simulator and visualization integrated together. However, because the visualization is packaged together with the simulator it is difficult to use the visualization independently or as a means to visualize network scenarios run in other simulators.

Number Systems	Number Processors	Simulated Nodes	Simulated Flows	Execution Time	Simulated Pkts
1	1	3766	3556	562 sec	36955410
1	4	15064	14224	697 sec	146014864
2	8	30128	28448	723 sec	291981440
4	16	60256	56896	769 sec	583689248
8	32	120512	113792	753 sec	1167925760
16	64	241024	227584	787 sec	2332761088
32	128	482048	455168	869 sec	4662689280

Figure 2.4: Modest GTNetS execution time increases as network scenarios increase in size [33]

2.1.4 OPNET. OPNET combines a network event simulator with a network event visualization for network packet events and node movement. The visualization includes node broadcast rings, node movements, and animated packets moving across wired links and wirelessly through user defined mediums. Although OPNET is a powerful network simulator suite it's proprietary implementation is significantly difficult to alter. Modifying OPNET's code requires an extensive knowledge of how the simulator works so that the right code is modified without corrupting OPNETs current tools. Also, in order for changes to OPNETs core to helpful across the simulator community, the changes must be implemented elegently so that they are easily installed on other user's OPNET suites. Figure 2.5 shows the OPNET visualization for a wireless network topology scenario. OPNETS full feature set make it a very attractive and potential candidate as a visualization tool, however, because it is proprietary it's usefulness is limited. The availability of open-source visualizations such

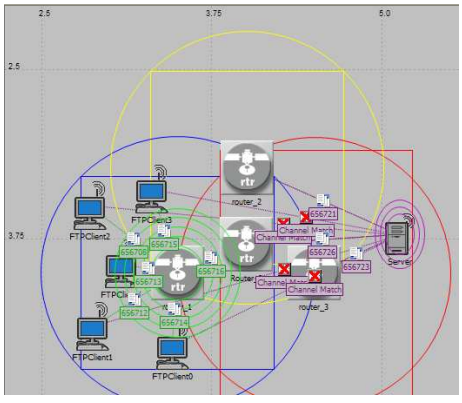


Figure 2.5: Multiple wireless nodes and wireless packets in OPNET network (broadcast range shown with large outer circles)

as Nam, GTNets, and the iNSpect has created a community that is not willing purchase proprietary software suites and is looking for a robust truly open-source network visualization framework.

2.1.5 Discussion. Nam and iNSpect are excellent compliments of one another. Based on their usefulness in both wired and wireless network visualizations the tools provide standards for what a network visualization should include. Additionally, the shortcomings of the visualizations give areas of improvement for future network visualization development. GTNetS is specialized simulator for simulating large network topologies. The simulator does a great job, but visualizing network traffic on large networks has limited utility. OPNET provides an excellent tool set for both network simulation and visualization. However much of the network simulator community is looking for more robust truly open-source network visualization solutions. This is shown by continued development and enhancement of existing open source visualizations.

Drawing on the successes and shortcomings of NAM, iNSpect, GTNets, and OPNET this research develops a new network visualization framework that visualizes both wired and wireless network events including: traditional packet animation across wired and wireless links, queue levels at each node, and dropped packets. Additionally, this framework sill provide new and better tools for not only observing network events but analyzing them. This research focuses on building these features to work with NS-2 trace files. However, the created framework design will also allow traces from other simulators to be visualized.

2.2 Visualization Toolkits

By using an existing visualization toolkit, the needed data structures commonly used for visualizations are provided in a well-designed and efficient package. Visualization toolkits facilitate quicker development of visualization framework features. This research examines several different visualization toolkits to determine the utility

for using them in the creation of a network visualization framework. The basis for toolkit utility is a collection of visualization functions, data structures, and organized animation logic that can be used and re-used by the visualization framework [13].

2.2.1 GUESS. The GUESS visualization toolkit highlights some specific aspects of graph visualization. Using the toolkit in a visualization gives users different ways to interact with a graph. In addition to the toolkit's graph visualization window GUESS provides a command window where text commands are entered using tailor-made command language (see Figure 2.6). These commands form the GUESS toolkit's visualization functions. Some of these functions include: altering layouts, graph-based clustering, and node coloring [1]. GUESS also uses underlying data structures and graph clustering functions from the JUNG [23] library. This library provides intuitive classes for both drawing and organizing graph nodes and links. GUESS animation logic is limited to features like force-directed layouts, panning, zooming, and modifying highlights/grouping. No underlying animation logic is available where actions can be defined by users to produce custom animations.

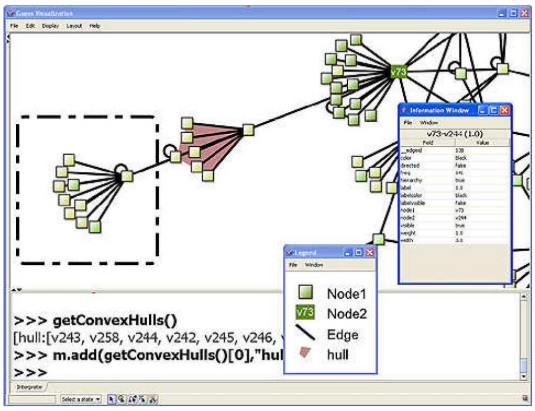


Figure 2.6: GUESS visualization illustrating command window, grouping, and graph layout [1]

2.2.2 Osprey. The Osprey visualization toolkit is used to build graphical representations of gene relationships [4]. The toolkit uses Java Standard Development Kit, but does not build on any known helper libraries. Because gene data sets

can be quite large Osprey implements a text query feature which alters visualizations based on query results (see Figure 2.7). In addition to queries Osprey defines numerous specific layout types to better organize data [30]. Research revealed little about how Osprey organizes data structures internally; however, this could be in part because the toolkit kit is proprietary and intimately connected with the BIOGrid [36] database. Osprey references the database for gene interaction data to render visualizations. Animations in Osprey are limited to mouse-over pop-up windows and layout modifications.

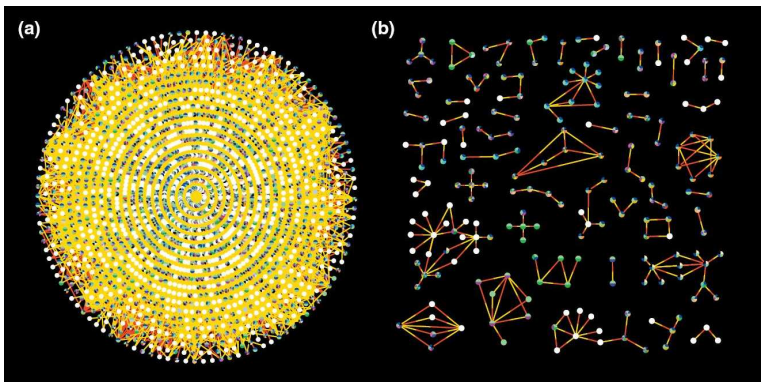
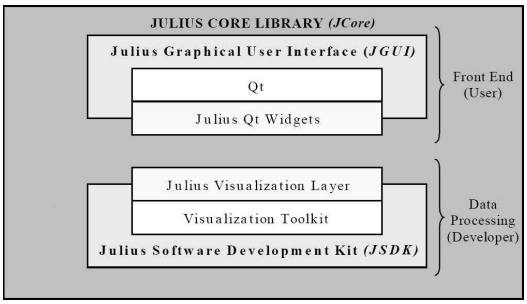


Figure 2.7: (a) Original graph visualization (b) resultant visualization after text query [4]

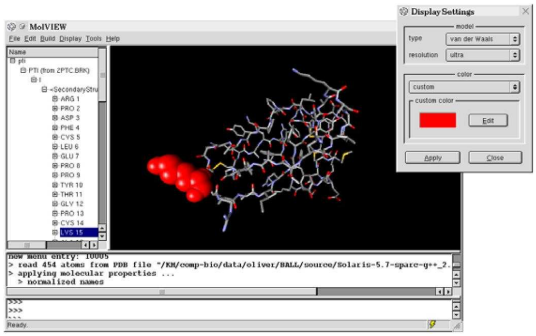
2.2.3 Qt. This comprehensive development framework includes an extensive array of features, capabilities and tools that enable development of high-performance, cross-platform rich-client and server-side applications [37]. The framework also includes a rich set of visualization development tools for user interfaces, layout management, 3D graphics, and scalable vector graphics [37]. The framework is available in both C++ and Java programming languages.

Research showed that most visualization frameworks using Qt employed the toolkit for user interfaces [15] [21] [29]. In addition to providing good user interface tools the toolkit allows users to use their own choice of graphical visualization toolkits as illustrated by BALL [25] (used for molecular modeling) and JULIUS [24] (used for medical imaging). However, all frameworks studied, except one, selected OpenGL as

their graphical visualization toolkit. This open-ended approach allows any visualization toolkit to be used which translates to great flexibility for an interface specific toolkit. Figure 2.8(a) shows the design of JULIUS and Qt widgets used to create the user interface for Ball (see Figure 2.8(b)). These examples reinforce the main use of Qt. Because of the emphasis on providing user interface tools Qt lacks the built in logic for network event animations.



(a) Julius framework conceptual overview illustrating use of Qt for user interface [24]



(b) Screenshot from Ball molecular modelar showing windows and widgets implemented with Qt [25]

Figure 2.8: Examples of Qt in Julius framework and Ball modelar

2.2.4 Piccolo. Piccolo is a toolkit that supports the development of 2D structured graphics programs, in general, and zoomable user interfaces, in particular. The toolkit maintains a hierarchal structure of objects and cameras, which allows the application developer to orient, group and manipulate objects in meaningful ways [20]. Piccolo uses a monolithic class hierarchy for organization of visualization information. This design results in smaller number of classes, however, top-level classes become

large and more difficult for developers to understand [3]. This design is illustrated in Figure 2.9 which show the base class PNode with no additional classes defining it's characteristics or behavior.

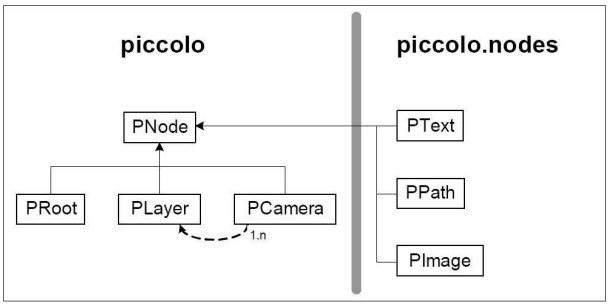


Figure 2.9: PNode class hierarchy showing monolithic Piccolo toolkit design [3]

The Piccolo visualization toolkit produces effective visualizations of data using tree and fisheye layouts which are easily adapted to user data. The tree layout gives users access to large amounts of hierarchal data, but presents it in a format which allows them to focus on particular areas of interest (see Figure 2.10). Fisheye layout gives user visibility to a large amount of data at a high level using a grid pattern. When users select an area of interest the layout reveals more detail (see Figure 2.11).

The Piccolo toolkit includes numerous beneficial functions that are helpful for visualizations. Piccolo also provides the necessary design and structure to support a network visualization framework. These features, along with a structured approach to adding custom animations, make Piccolo a good toolkit to use with the network visualization framework. The only drawback of Piccolo is the monolithic design approach. This approach creates large top-level classes. Expanding the framework then requires sifting through lines and lines of code to add functionality to the major top-level classes of the toolkit. Because it is anticipated that this framework will be expanded through future research the monolithic Piccolo toolkit is less desirable.

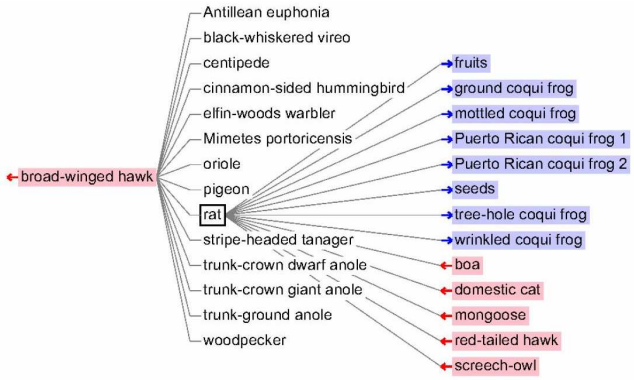


Figure 2.10: Interactive graph expanded when users click on an entry [28]

Figure 2.11: Interactive grid layout (called fisheye) where users click on a cell to reveal more detailed information [3]

2.2.5 ***Prefuse.*** ***Prefuse*** is an extensible software toolkit for helping software developers create interactive information visualization applications using the Java programming language. ***Prefuse*** simplifies the processes of data handling, representation, and mapping to on-screen displays as well as crafting direct manipulation interactions with the visualization [16]. The ***prefuse*** visualization toolkit is well designed and supported. SourceForge.net hosts online support through a user forum with a large number of ***prefuse*** developers including the toolkit's author Jeffrey Heer.

The ***prefuse*** toolkit follows the model-view controller design pattern. The The ***prefuse*** `action`, `render`, and `display` packages constitute the view and ***prefuse*** `control` and `data.query` packages make-up the controller. Figure 2.12 shows a high level view of the ***prefuse*** toolkit and highlights the model-view controller design pattern elements. ***Prefuse*** organizes data structures into two main hierarchies: the `Tuple` and `TupleSet` interfaces. From these two interfaces branch all the concrete

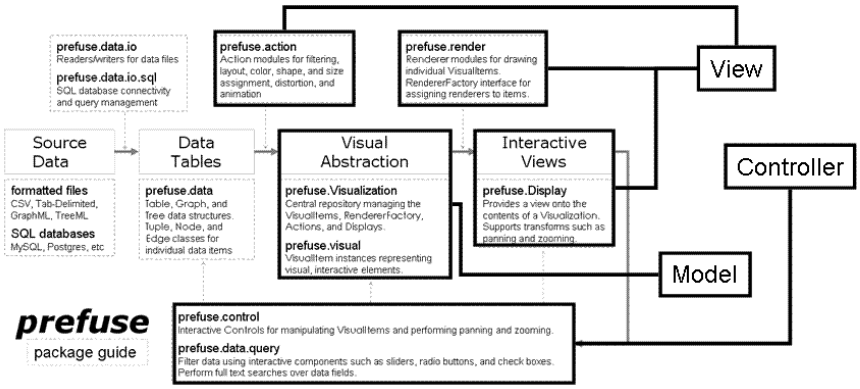


Figure 2.12: ***Prefuse*** toolkit with Model, View, and Controller highlighted

data structures (see Figure 2.14) and collections of data structures (see Figure 2.13) that form the ***prefuse*** model

Prefuse provides a rich polylithic class hierarchy of data structures to define visualizations [17]. ***Prefuse*** data structures include the commonly used structures graphs, tables, edges and nodes. `VisualGraph`, `VisualTable`, and `VisualItem` are superclasses of these data structures and contain important display information. `VisualGraph` defines the topology of the network (nodes and edges) and `VisualTable` holds a collection of `VisualItem` representing packets in the network. Modifying the Visual objects creates a corresponding change in how the ***prefuse*** visualization toolkit renders each object on screen.

2.2.6 Discussion. The visualization toolkits discussed in this section were all developed for different reasons. The toolkits that best match the requirements for a network event animation framework are Piccolo and ***prefuse***. The other toolkits provide the data structures and even the visualization functions needed, however what they lack is the organized logic to create customized visual animations. Piccolo and ***prefuse*** both provide these features.

Piccolo and ***prefuse*** visualization toolkits vary fundamentally in how they are implemented. The Piccolo monolithic implementation creates top heavy bas classes while the ***prefuse*** polylithic design distributes logic across different classes. The

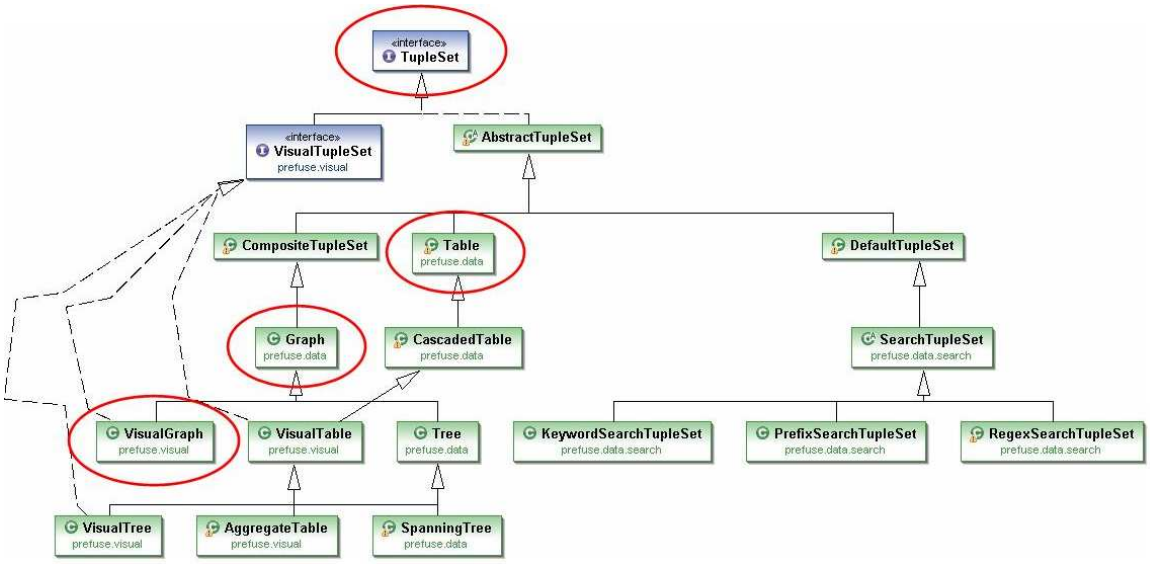


Figure 2.13: ***Prefuse*** `TupleSet` Hierarchy: Shows how ***prefuse*** organizes collections of visual and data objects used to create a visualization

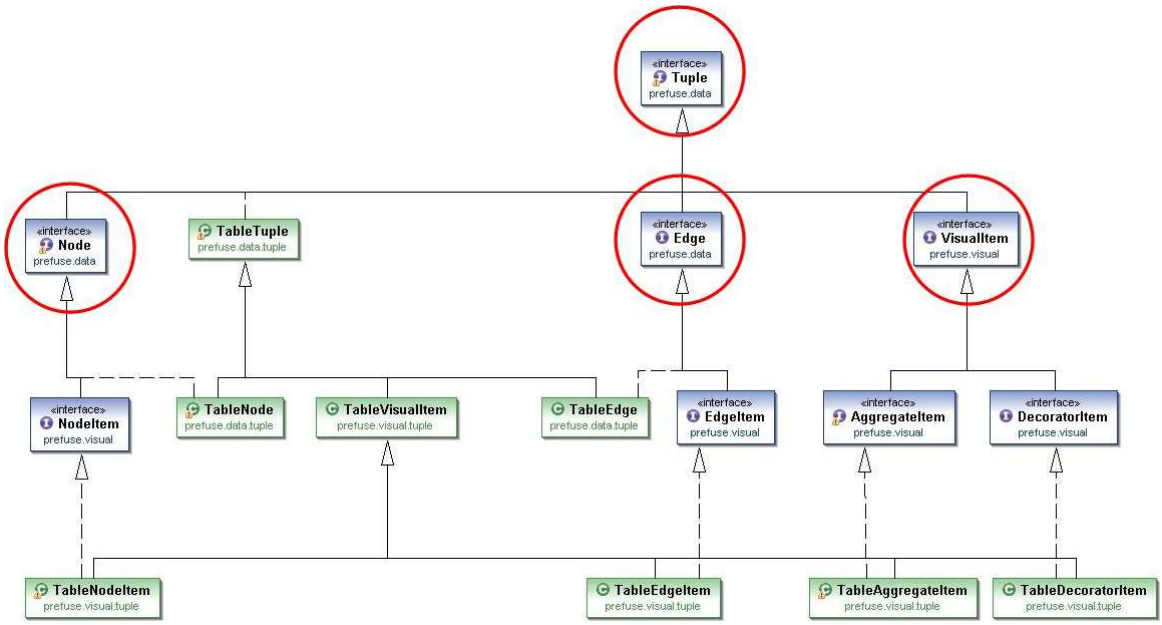


Figure 2.14: ***Prefuse*** `Tuple` Hierarchy: Shows how ***prefuse*** organizes individual pieces of visualization data

multiple class approach of ***prefuse*** was a better fit for this development because the polylithic class hierarchy allows for implementing different behaviors for the main visual objects on screen: nodes, links, and packets. Specifically, nodes and links can use the ***prefuse*** node and edge java interfaces and packets can use the generic ***prefuse*** `VisualItem` interface. The node, link, and packet functionality could have simply been added to the existing Piccolo classes, but this would have required additional implementation not needed with the ***prefuse*** toolkit. Also, it is anticipated that in the future additional visualization features will be added to this implementation. Therefore, this research uses the ***prefuse*** visualization toolkit to create a new network visualization framework.

III. Visualization Framework Design and Implementation

The design and implementation of this network visualization framework utilizes the iterative process for software development applying design patterns where applicable. This process also implements refactoring techniques to keep code implementation clean. The four major design challenges for this framework are: trace file format, network simulator trace file parsing, wired/wireless network event animation, and creating a visualization interface to alter network simulator parameters during runtime.

Understanding the ***prefuse*** visualization toolkit design is crucial to addressing the four major design challenges for the network visualization framework. Figure 3.1 illustrates how the ***prefuse*** toolkit performs data visualization. The toolkit design is perfect for addressing the previously mentioned design challenges. ***Prefuse*** data corresponds to a trace file. ***Prefuse*** filtering is accomplished through a file parser, which parses data into the ***prefuse*** visual forms. The ***prefuse*** rendering and view handles the challenge of animating network events. Finally, the user interacts with the ***prefuse*** user interface controls to provide user interaction with the visualization. Because ***prefuse*** addresses these challenges it is an excellent toolkit to extend into this network visualization framework.

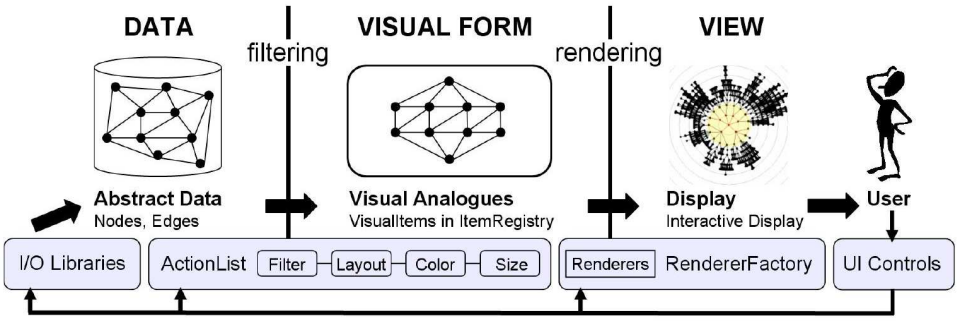


Figure 3.1: The ***prefuse*** visualization toolkit. Lists of composable actions filter abstract data into visualizable content and assign visual properties (position, color, size, font, etc). Renderer modules, provided on a per-item basis by a `RendererFactory`, draw the `VisualItem` to construct interactive Displays. User interaction can then trigger changes at any point in the toolkit [18].

3.1 Network Trace File

The network visualization framework requires a trace file produced by the network or network simulator to visualize network events. The initial, and majority, of simulator traces used for this research came from NS-2. GTNetS produces a trace file, however, this file is primarily used to record network statistics, not unique network events [33]. OPNET uses it's own network visualizer and therefore does not, by default, produce a trace file. However, OPNET can be configured to produce a trace file of network events according to a specified format. Because NS-2 produces trace files with the needed network event information this research focuses initially on parsing trace files from NS-2 and later extend to other formats.

3.2 Trace File Parser

NS-2 can produce produce a trace file during a network simulation in several different formats. This research initially focuses on NS-2 traces use by Nam. These traces follow certain format conventions, but can still have subtle variations based on user configuration of NS-2 [8]. Figure 3.2 shows an example of and NS-2 trace that could be visualized by Nam.

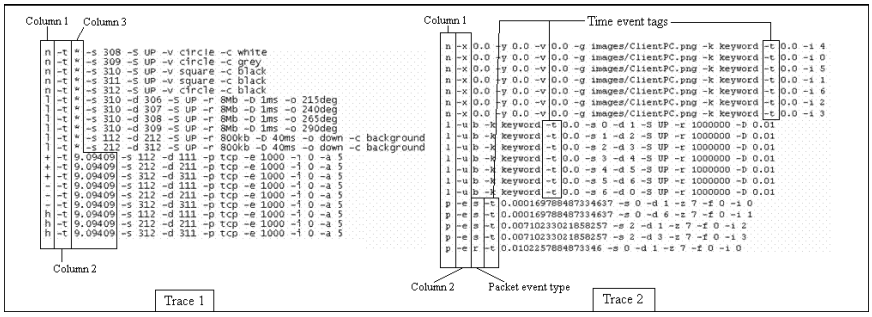


Figure 3.2: NS-2 trace samples, showing two formats highlighting the differing locations of time and other tags

Each line in the Figure 3.2 is a network event. The first character in each line classifies it as a node, link, or packet network event (column 1). Within each network event line are tags denoted by the '-' character followed by a letter; these tags specify information about a network event. Common to all network events is the time event

tag, denoted as '-t' (see Figure 3.2), indicating when an event occurred. The time event tag illustrates one of the differences in the two trace files. In Trace 1 the tag is consistently in column 2, but in Trace 2 the location of the tag varies between three different columns (see Figure 3.2).

The major difference between the two trace files is the packet network event lines. The events differ greatly because Trace 1 tells us more about packet events than Trace 2. The table below lists tags corresponding to packet event NS-2 trace lines.

Nam Visualization Packet Events	
+	Packet is queued in a node
–	Packet is dequeued from a node
h	Packet begins transmission across a link
r	Packet is received by another node
d	Packet is dropped from node queue (queue overflow)

[8]

Trace 2 does not describe packet queuing or dequeueing, but only describes packets being sent and received. Additionally, Trace 2 defines another network event tag '-e' (Trace 2: column two). Following the tag are the character 's' or 'r' indicating a packet was sent or received. The two different trace files illustrate the challenge of creating a trace file parser capable of parsing NS-2 trace files with subtle differences in tag placement and meaning.

3.2.1 Initial Design. The network visualization trace file parser communicates directly with the ***prefuse*** visualization toolkit. This communication uses the Data column pattern implemented in the ***prefuse*** toolkit [2]. Figure 3.3 illustrates the data column pattern. Collections of columns compose a table. and when a column is added to a table the `ColumnFactory` creates the column in the table and returns a reference to that column. A Table is used to obtain a reference to a given column. When a value in a column is altered the `columnChanged` method is invoked and tables that share that column are notified of column changes.

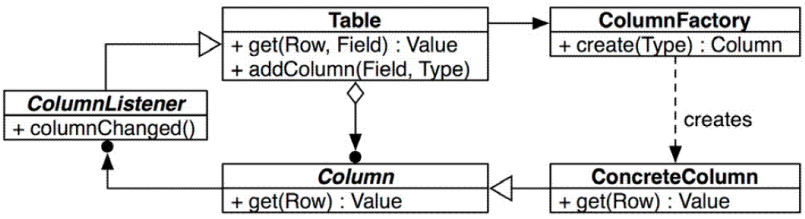


Figure 3.3: Data Column Pattern

The network visualization trace file parser uses references to three ***prefuse*** tables each holding network node, link, and packet information respectively. Each row in a ***prefuse*** `Table` object corresponds to a single item to be visualized, a `VisualItem` object. A column, however, corresponds to a specific data attribute for a collection of similar `VisualItem` objects displayed by the visualization. `Column` objects in ***prefuse*** `Table` objects must be assigned, at creation, a specific type and value. To assist with `Column` type and value assignment ***prefuse*** uses a `ParserFactory` object to sort incoming visualization data into specific types (Integer, Double, Float, String, etc.). `ParserFactory` sorting is a two-step process. First, the `ParserFactory` sample method is called to decide the correct type of the string input and second, the `getParser` method is called which returns a specific parser for the input type. The returned parser provides the necessary information to store value and type information into a ***prefuse*** `Column` object; and even create a `Column` object when necessary.

The data parsing process described above utilizes the factory method pattern and the observer pattern. The factory method pattern is used in both the `ColumnFactory` and `ParserFactory`. `ColumnFactory` uses the create method to instantiate a concrete product which is a subclass of Column. `ParserFactory` does the same with the `getParser` method which returns a `DataParser` subclass [13]. Finally, the observer pattern is used by `Table` implementing the `ColumnListener` interface. This interface defines the `columnChanged` method allowing a `Table` to notify other `Table` objects that share this column [2].

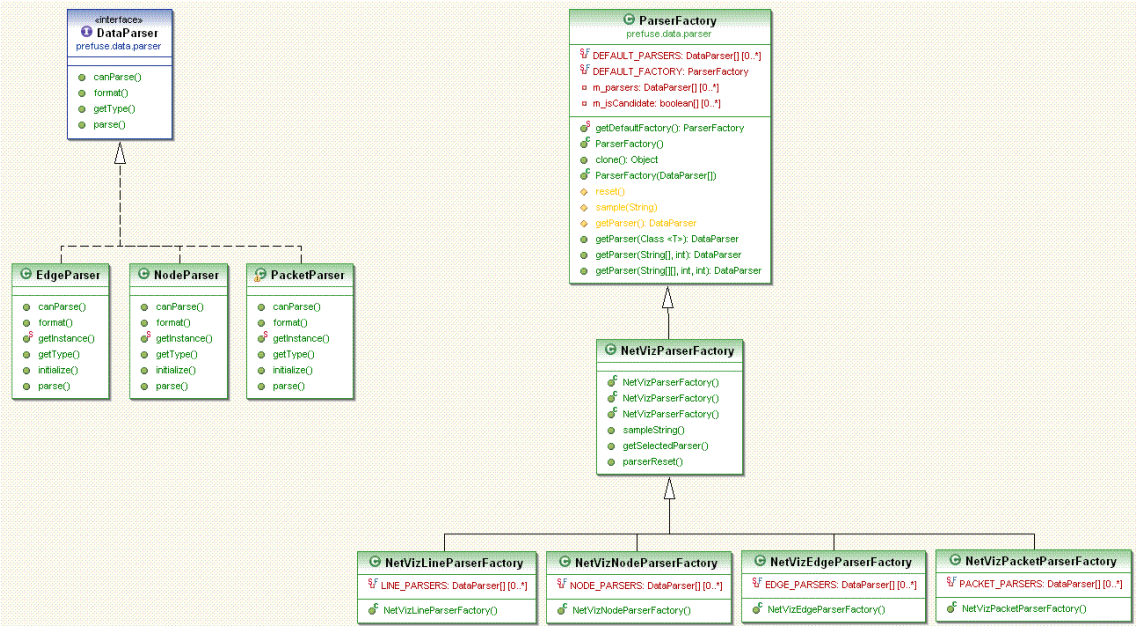


Figure 3.4: Extension of ***prefuse*** `DataParser` and `ParserFactory` into network visualization specific parsers and parser factories

The trace file parser design extends the relationship between the ***prefuse*** `Parser Factory` and `ColumnFactory` to handle the specific needs of parsing network events. Figure 3.4 shows the extension of the ***prefuse*** `ParserFactory` into specific `Parser Factory` subclasses for different possible network events. This design separates code between the different network events allowing each implementation to tailor the way it parses information. Each network event specific `ParserFactory` uses an array of node, edge, or packet parsers, extending the `DataParser` interface, to parse their respective relevant data from the trace file. Additionally, the node, edge, and parser factories retain the elements of the ***prefuse*** `ParserFactory` making them capable of parsing types (Integer, Double, String, etc..). This design follows the factory pattern design pattern where `DataParser` serves as the interface but instantiation is left to the subclasses (line, node, edge, packet `ParserFactory)` subclasses [12]. This design is show in Figure 3.5.

3.2.2 Initial Design Problems. The initial file parser design built an architecture that extended the ***prefuse*** `ParserFactory` to create specific parser factories

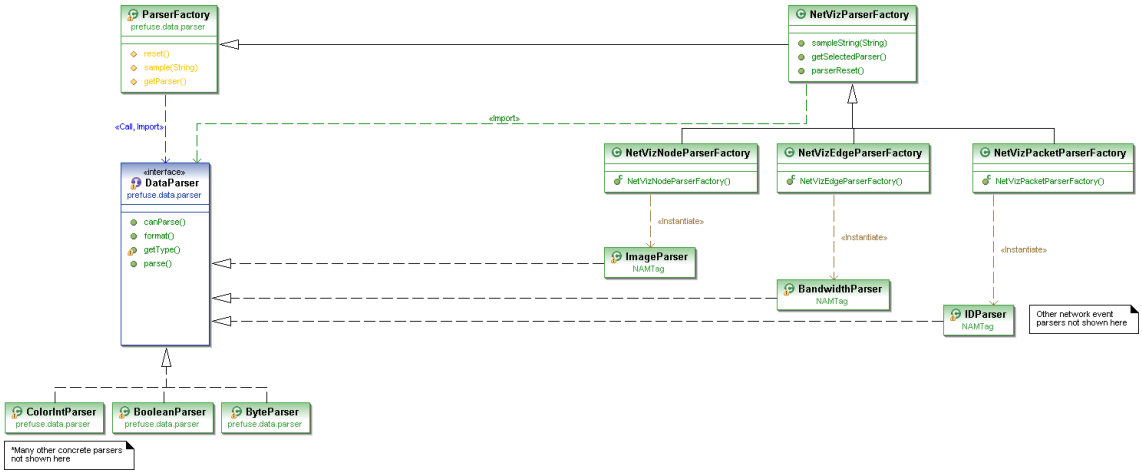


Figure 3.5: Creation of network visualization specific parsers `ImageParser`, `BandwidthParser`, and `IDParser`

and separate parser objects extending the ***prefuse*** `DataParser` interface (Figure 3.4). This design gave users the ability to create, modify, and extend parser classes and created parser factories based on information found in a specific trace file (see Figure 3.5). The initial parser design also created a class hierarchy that utilized polymorphic method invocation to parse each trace file line. Polymorphic methods allowed line parsing to proceed under different criteria as specified by different user-defined parser objects. This robust parser architecture provided the ability to add new parsing criteria by simply inserting new parser classes into the class hierarchy as shown in Figure 3.5. Extending the `DataParser` interface allowed the framework to function the same way no matter how the parser objects actually parsed the lines. These design decisions were a good mix of using existing code from the ***prefuse*** toolkit and giving flexibility to the user to extend ***prefuse***'s parsing capabilities according to the trace file.

The design, however, created undesired side effects. The parser hierarchy and associated helper classes produced extra coupling to ***prefuse*** data structures storing visualization information. Figure 3.6 illustrates the high coupling centered around the `EdgeTableManager` class (similar results were found in `NodeTableManager`). In addition to the increased coupling further exploration into the trace files used revealed

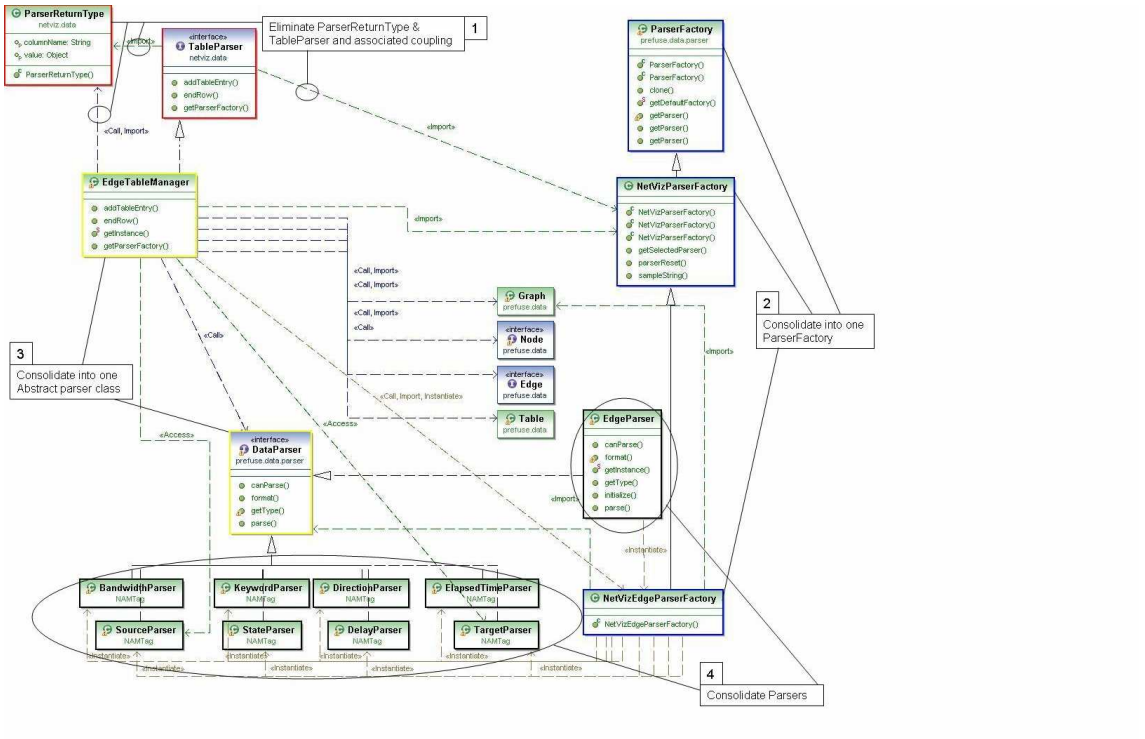


Figure 3.6: Initial Parser Design

relatively few subtle changes between traces. This discovery along with the high coupling of the initial design motivates a more simple parser design.

3.2.3 Final Design and Implementation. The final parser design builds on the initial design, but effectively reduces the coupling in a simple elegant design (see Figure 3.7). The design replaces the old `NetVizParserFactory` hierarchy (see Figure 3.4) with one `ParserFactory`. This change creates one consolidated location for specifying parser criteria, making parsing changes simple and straightforward. In addition to the `ParserFactory` the concrete products are limited to only node, edge, and packet parser objects. Finally, the Parser abstract class handles updates to the visualization through the node, edge, and packet parser objects. This design establishes parser as the central manager for updates to different objects held in the ***prefuse*** visualization framework.

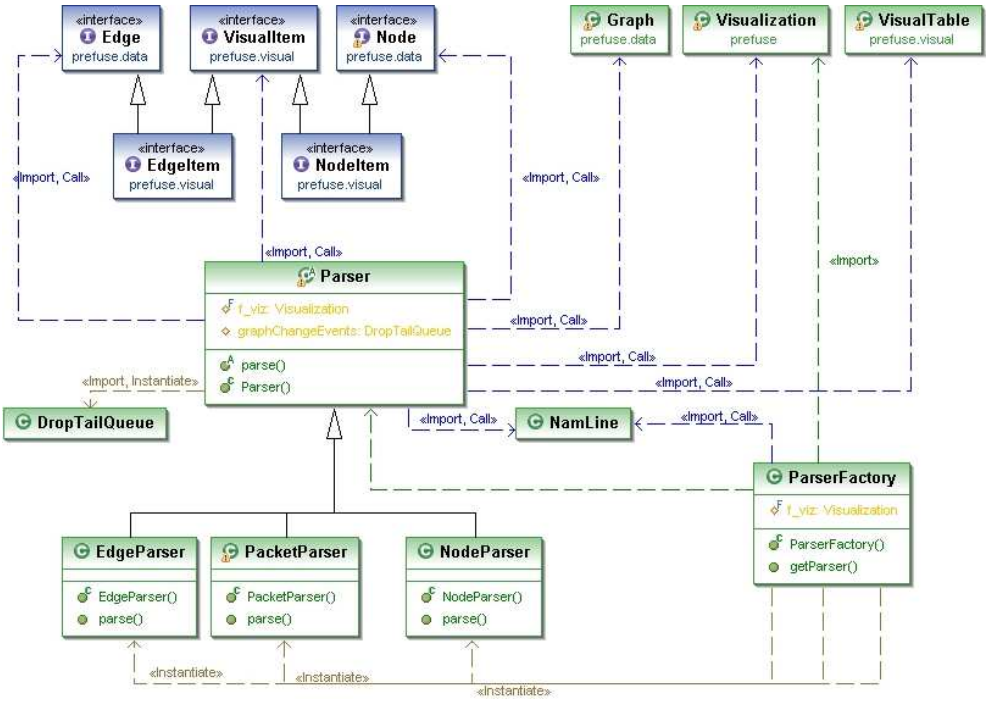


Figure 3.7: Final Parser Design

3.3 Network Event Animation

Chapter 2 discussed the common data types used in the ***prefuse*** visualization framework (see Figure 2.13 and Figure 2.14). However, equally important to defining visualization data types is having a framework to handle the display and animation of data as it changes throughout the visualization. The final network event animation uses implementation from both ***prefuse*** and new code written. The initial implementation displayed and animated ***prefuse*** `VisualItem` data types to visualize NS-2 trace files simulating network events for a wired network. However, the final implementation includes visualization of wireless network events.

3.3.1 Wired Networks. Figure 3.8 shows the network event animation design. Central to the design are the `NetVizDisplay` and `VisualizationControl` objects. Both objects handle separate portions of the network event animation.

The `VisualizationControl` object handles the majority of the network-specific visualization logic. Two main threads assist with this implementation:

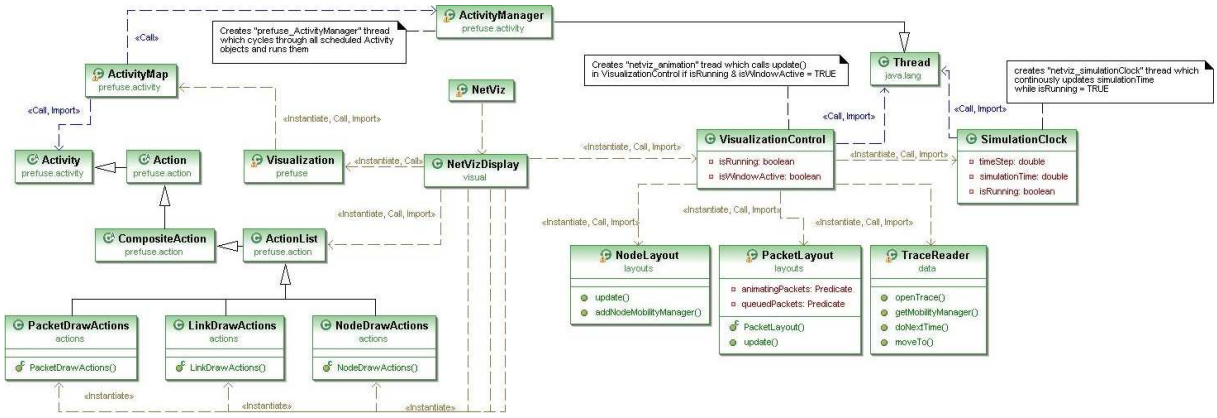


Figure 3.8: Network Event Animation Design

'netviz_animation' and 'netviz_simulationClock'. The 'netviz_animation' thread reads a line from the trace file, parses it into the `Visualization` object, and updates the layout of all node and packet `VisualItem` objects in the visualization. The 'netviz_simulationClock' keeps track of the virtual clock in the visualization. This clock is displayed on screen during the visualization and must remain synchronized with network events as read from the trace file. Additionally, the thread coordinates user interaction with the on screen timer bar (see Figure 3.9) to ensure the visualization remains synchronized with the virtual timer.

The `NetVizDisplay` object interacts directly with the ***prefuse*** `Visualization` object and the `VisualizationControl` object to display the visualization of network events. `NetVizDisplay` creates the `Visualzation` object which creates the 'prefuse_ActivityManager' thread. This thread constantly checks the ***prefuse*** `Activity Map` for `Activity` objects defining actions to be displayed in the visualization. In addition to creating this thread `NetVizDisplay` defines node, link, and packet `DrawActions` and loads them into the `prefuse ActivityMap`. The defined node, link and packet `DrawActions` render visualization information to the screen when notified by the `ActivityManager`.

`VisualizationControl` and `NetVizDisplay` work together to animate packets moving across links from node to node (see Figure 3.9). This animation is accom-

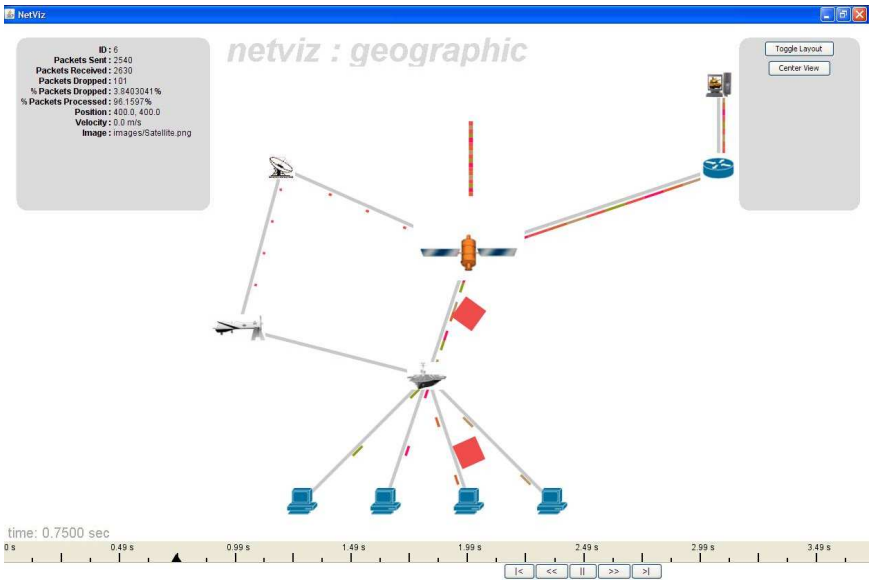


Figure 3.9: Network Event Animation Screen shot

plished with both the update method in `PacketLayout` and the `PacketDrawAction` method in `PacketDrawAction` (see Figure 3.8). `PacketLayout` defines which `VisualItem` packets need new x,y coordinates and assigns new coordinates, which the `PacketDrawAction` renders to the screen. The result is a design that effectively leverages the `VisualItem` and `ActivityManager` objects inside ***prefuse*** to create a network event animation.

3.3.2 Wireless Networks. Visualizing wireless network packet transmission is different from wired network packet transmission in two ways. First, wireless nodes often move while transmitting and receiving data. Second, the very nature of wireless packet transmission is fundamentally different than wired transmission. A wired packet is directed to the next node hop on the link. However, wireless packet transmissions (from nodes with omnidirectional antennas) are not constrained to one next hop on their path. Wireless packets are broadcast and can be received by many different nodes. Nodes that receive the broadcast can ignore it, process the packet, or relay the packet to surrounding nodes. This understanding of wireless packet traffic raises the question: How do we visualize wireless traffic? An important consideration when

answering this question is how much detail to show [19]. Accurate visualizations of transmission energy rings disseminating from a node quickly becomes confusing and does not highlight a packet's route movement from source to destination. However, the nature of wireless broadcasts does not allow a packet's final destination to be known at the time of initial packet broadcast. Despite these challenges this research creates an accurate wireless network visualization which addresses node movement and packet transmission, using the following techniques.

3.3.2.1 Node movement. Node movement is critical for effective network visualization observation and analysis. Increased use of mobile nodes in networks warrant the need to accurately show mobile node movement. Visualizing node movement is an important part of understanding why a network is performing the way it is. Mobile nodes present network performance challenges not encountered in traditional wired networks. First, node movement can cause network reliability to degrade. As nodes move farther away signals can degrade or be obstructed which, depending on the node, can have effects that ripple through the entire network. Second, node movement can result in complete loss of the node due to compromise, destruction, or node defect. Without node position the correct recourse cannot be taken. Finally, there is little point in a network visualization if the picture is inaccurate–physically moving nodes simply must move within the visualization. These factors establish accurate node movement as an essential part of a network visualization framework.

The network visualization requires that node movement information be given in the trace file using the defined tags -u (x-coordinate velocity), -v (y-coordinate velocity), -T (duration of movement) [8]. The tags must be placed inside node event lines in the file, therefore every node movement must correspond to a specific node event. Figure 3.10 shows a trace file segment highlighting three nodes. Initially the nodes are given no movement by setting velocity and duration of movement tags to zero. Later in the trace, however, these nodes are assigned node movement with specific node speed, direction, and duration of movement (see Figure 3.10.

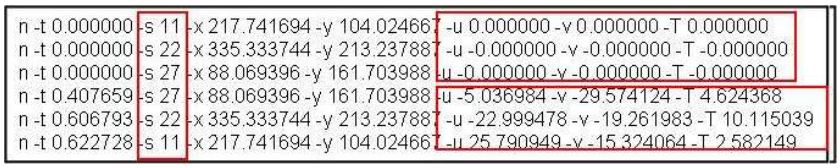


Figure 3.10: Node events inside a NS-2 trace for three different nodes initially no node movement defined, but later node movement is specifically defined by the -u (x-coordinate velocity), -v (y-coordinate velocity), -T (duration of movement) tags. layer

Node movement information is parsed out of the NS-2 trace file into a new objects called `MobilityEntry`. Each of these objects correspond to specific node movement, because many specific node movements may occur within a trace file all `MobilityEntry` objects are managed by by the `NodeMobilityManager`. The `NodeMobilityManager` object is added to `NodeLayout` to update node position each time the `NodeLayout` update method is called by the 'netviz_animation' thread (see Figure 3.8). Inside the `NodeLayout` object the current simulation time is used with the specific node movement information inside `MobilityEntry` objects to calculate the correct position of the node at the current time. This implementation follows closely the implementation used to produce packet animation with `PacketLayout` discussed previously. Based on node movement information held in `MobilityEntry` objects the 'netviz_animation' thread updates node position to create node movement. Figure 3.11 shows the network visualization framework design for implementing node movement.

3.3.2.2 Wireless packet transmission. In order to understand the difficulties of visualizing wireless network events Figure 3.12 shows four specific wireless traces illustrating the problem of wireless traffic visualization. Each sample trace contains network events for a unique packet shown by the id number following the '-i' tag in each sample. 3.12(d) shows a major deviation from wired packet traffic. Instead of specifying the destination after the '-d' tag a '-1' indicates the packet is broadcast from node two. 3.12(b) illustrates packet traffic moving from wired links to a wireless link. The first receive clearly shows the source as one and the destination as two.

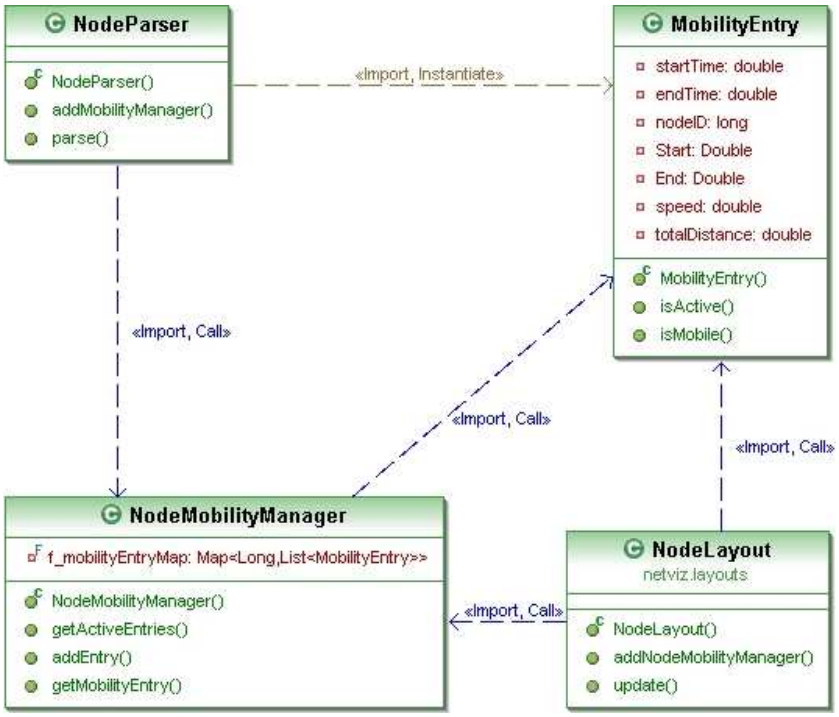
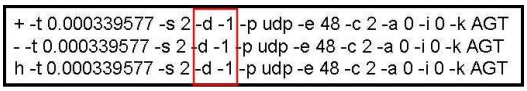


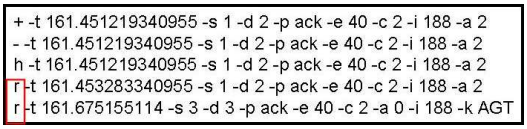
Figure 3.11: `NodeParser` parses node event trace lines and updates data fields inside `NodeMobilityManager`. `NodeLayout` then accesses a set of `MobilityEntry` objects inside `NodeMobilityManager`to correctly animate node movement.

However, the second receive is at node three without a previous send event. 3.12(c) shows wireless- node-to-wireless-node packet transmission. Here a queue, dequeue, and send event from node four are followed immediately by a queue event at node three, indicating a receive event at node three without a receive event entry in the trace file. Finally, 3.12(d) shows a queue, dequeue, and send event from node one followed by a receive event at node two. This trace sample contrasts 3.12(c) which does not include a receive event. Because of the ambiguous nature of NS-2 trace files for wireless packet events this network visualization framework pre-processes trace file data. By pre-processing trace data users can visualize wired and wireless network traffic accurately and without confusing wireless broadcast rings. It also gives users the ability to visually track packets from source to destination.

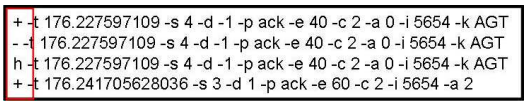
3.3.2.3 Trace file pre-process methodology. Nam network visualizations show animated wireless transmission energy rings to denote a wireless trans-



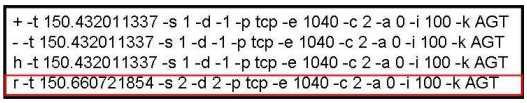
(a) Wireless packet events queue, dequeue, and send where the -d tag does NOT indicate the packet's final destination



(b) Packet received at node two, then received at node tree without wireless broadcast



(c) Wireless packet broadcast from node four, but no receive event at node three only a queue event



(d) Wireless broadcast from node one, then receive event at node two with -s tag two rather than one

Figure 3.12: Wireless traces of four unique packetIDs

mission. A trace file send event with destination tag '-d -1' indicates the node and the time a wireless broadcast occurs. However, the information needed to visualize wireless packet transmission as packets moving from node to node is not contained in this one line as shown in Figure 3.12. This information is only contained in later lines in the trace file when the packet's ID shows up in a receive event. There is no way to begin animation of a wireless packet at the time of the send event. In order to know both from where a packet is sent as well as where it is going, many trace line events must be considered. This requires the visualization framework to pre-process trace files, calculate a wireless packet source and destination(s), and store the information so the 'netviz_animation' thread can know the packet destination(s) when is begins animating a wireless broadcast.

The visualization framework uses a map-like data structure to store needed trace data during the read-ahead. Figure 3.13 shows the basic design of the data structure. The outer map uses each broadcasting node throughout the trace as keys. These keys map to an inner map where each packetID is used as a key for a set of destination node IDs. This structure is necessary to allow nodes to broadcast multiple times to multiple destinations—all wireless network traffic possibilities.

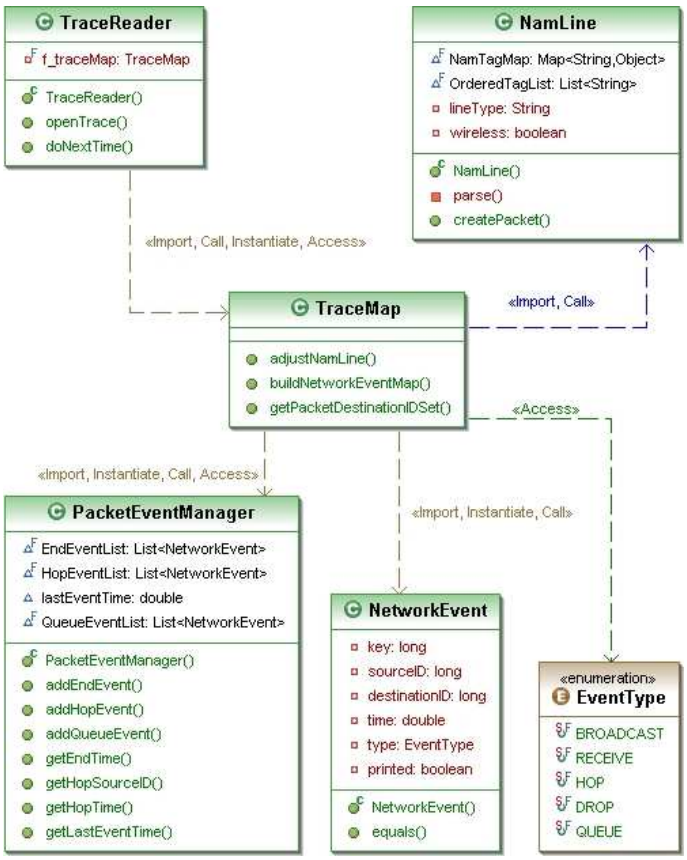


Figure 3.13: Data Structure design for wireless traffic Map. The map stores routes for wireless packets from source to destination for later visualization

3.4 Visualization / Simulator Interaction

Design concepts discussed to this point, do not address interaction with the simulator. Establishing a communication link with an external simulator and passing new trace information to the visualization parser through the link is a major implementation challenge. The following outlines a design for this implementation.

The Gateway pattern provides a simple and effective template to access external resources and is a good fit to access an external network simulator [10]. The initial design creates the `VisualizationGateway` and `SimulatorGateway` classes to handle communication with the simulator. The `VisualizationGateway` encapsulates all functions the network simulator will call to effect the Visualization. These methods primarily involve transmitting new trace data. The `SimulatorGateway` encapsulates all methods the visualization will call to effect the simulator. The methods notify the simulator of user interaction with the visualization (taking down links, moving nodes, etc.) that will effect the results of the simulation. Critical to the success of the Gateway pattern implementation are simulator utilities currently being developed by members of the AFIT hybrid communication team. These utilities will accept visualization input, alter the simulation and return the new trace through the `SimulatorGateway`.

3.5 Code Refactoring

Refactoring is the process of changing a software system in such a way that it does not alter the external behavior of the code yet improves its internal structure [9]. This research included three major refactorings: First, the extract class refactoring removed many similar methods from the large `TraceReader` class into a new `NamLine` class. Second, a conditional chain used for parsing was replaced by parser subclasses using polymorphic calls to parse strings differently. Finally, extract hierarchy refactoring was implemented as a side-effect of applying the two previously mentioned refactorings.

3.5.1 Extract Class [9]. The initial network visualization implementation used the class `TraceReader` to handle connecting, parsing, sorting, and loading information into the vizualization tables. This implementation created what the authors of [9] call 'bad smells in code'. One such smell was a large `TraceReader` class. The `NamLine` class removed 'helper' methods methods for extracting information from a

new trace string created in `TraceReader`. Additionally, it created a more object-oriented design placing all methods relating to extracting trace information in one place.

3.5.2 Replace Conditional with Polymorphism [9]. Another 'code smell' in the code was conditional chains. One such chain is shown in Figure 3.14. The Parser implementation shown in Figure 3.7 replaces the conditional chain with polymorphic calls to the Parser subclasses `NodeParser`, `EdgeParser`, and `PacketParser`. Again, this design reduced the size of `TraceReader`, but it also made the code easier to extend as new parsers need only extend Parser. Figure 3.14 shows the polymorphic parse call.

```
private void initialParse() throws IOException {
    boolean pastSetup = false;
    NamLine line = null;
    while(!pastSetup) {
        line = new NamLine(in.readLine());

        if(line.isCommentLine()) continue;

        if(line.getTime() > 0.0) {
            pastSetup = true;
        } else {
            if(line.isPacketLine()) {
                parsePacket(line);
            } else if(line.isLinkLine()) {
                parseConnection(line);
            } else if(line.isNodeLine()) {
                parseNode(line);
            }
        }
    }
    nextLine = line;
```

```
private void initialParse() throws IOException {
    boolean pastSetup = false;
    NamLine line = null;
    Parser lineParser =  null;
    while(!pastSetup) {
        line = new NamLine(in.readLine());

        if(line.isCommentLine()) continue;

        if(line.getTime() > 0.0) {
            pastSetup = true;
        } else {
            lineParser = f_parserFactory.getParser(line);
            if(lineParser != null) {
                lineParser.parse(line);
            }
        }
    }
    nextLine = line;
}
```

Figure 3.14: Conditional Chain Example

3.5.3 Extract Hierarchy [9]. The hierachy that facilitates the polymorphic method parse also creates the extract hierarchy refactoring. As with Design Patterns certain refactorings seam to occur automatically as a result of implmenting others. Software development is naturally prone to errors. Refactoring can significantly reduce errors during software development and produce more maintainable code. [31].

3.6 Discussion

The network visualization framework discussed above creates an intriguing new way to study wired and wireless networks. Research on network protocols and network design will be aided by the ability to see wireless network traffic and communicate with network simulators. Additionally, because this framework is built on the ***prefuse*** visualization toolkit new animations can be added through new ***prefuse*** Action objects. The network visualization framework provides new visualization capabilities and a good design for future development.

IV. A Network Visualization Framework for Network Event Observation and Analysis

This research produced a network visualization framework that advances network event analysis capabilities. The new framework includes the architecture necessary to parse NS-2 trace files, but can be expanded to parse trace files from other simulators. This capability allows the framework to visualize network scenarios run on different simulators and compare the results. Another framework capability is the robust and easily extensible design used to layout the network topology and animate network events within the visualization. This design gives developers the ability to define custom network topology layouts and network event animations to highlight specific analysis objectives. The framework empowers the visualization with precise user interface controls including: zooming, panning, node highlighting, and visualization timing controls. Finally, the visualization shows promise towards allowing users to alter a network simulator scenario (e.g., toggle node or link status between up and down) by interacting with the visualization.

Visualizations, by their very nature, are difficult to test. This research tested numerous visualization scenarios by visual inspection. The testing was done by visualizing a network scenario, or trace file, in Nam and comparing the resultant visualization with the same trace file visualized by this framework. The network scenario trace files used during framework testing demonstrate important network event visualization capabilities.

4.1 Robust Parser Architecture

Creating a robust parser architecture for parsing network simulator trace files requires some knowledge of how trace the file data is organized. Therefore, this framework starts with four basic trace file parsing assumptions. First, trace file data is organized by individual network events and each network event corresponds to a line in the network simulator trace file. Second, each network event line in the trace file is marked as a node, link, or packet event. Third, after the network event identifier

the remainder of the network event line is composed of identifier tags and data. Finally, all network event lines are in chronological order as they occurred during the simulation. Based on these assumptions this framework has created the `TraceLine` abstract class. This class accepts a `String` trace line event and provides methods to return common trace line event tags contained in the `String`. This effectively saves each trace line event as a `String` and then parses the string to retrieve specific data corresponding to trace line event tags. Classes extending `TraceLine` override and supplement the `TraceLine` base methods to produce new parser functionality and create the capability to accept multiple trace file formats.

`TraceLine` implementation uses a Java `Map` with parameterized types `String` and `Object` to organize the mapping of trace line tags to their corresponding data. By using a general map data structure no assumptions are made about specific tag names or data types. Trace event line parsing and tag data retrieval from `TraceLine` subclasses is completely customizable by overriding the `parse` method and adding or overriding data retrieval methods. The `TraceLine` abstract class implementation makes multiple trace file parsing a simple matter of extending `Tracline`.

Utilizing the toolkit developed by Mark Coyne for OPNET and the `TraceLine` abstract class this framework visualizes an OPNET network simulator scenario [6]. Figure 4.1 shows the trace file produced by OPNET that follows this framework's parsing criteria explained earlier. However, trace tags used in Figure 4.1 slightly differs from what was used in previous trace files reviewed in this framework research. Despite these differences the framework parser is able to easily adapt to the changes

```
n -t 0.000000 -i 1 -x 10.0000 -y 10.0000 -v 0.000000
n -t 0.000000 -i 2 -x 20.0000 -y 10.0000 -v 0.000000
l -t 0.000000 -s 1 -d 2 -u b -r 96000 -l 1 -S up
p  -e s -t 199.431511 -td 199.474011 -c 199.431511 -i 1 -z 248 -s 1 -d 2 -a 199.506403
p  -e s -t 199.506403 -td 199.548903 -c 199.506403 -i 3 -z 248 -s 2 -d 1 -a 199.581295
p  -e s -t 199.581295 -td 199.620462 -c 199.581295 -i 5 -z 216 -s 1 -d 2 -a 199.652854
p  -e s -t 199.620462 -td 200.086295 -c 199.581295 -i 1  -z 4312 -s 1 -d 2 -a 200.118687
p  -e s -t 200.168688 -td 201.424521 -c 200.168688 -i 27 -z 11896 -s 2 -d 1 -a 201.456913
```

Figure 4.1: Trace created by OPNET toolkit. Highlighted are the packet event lines beginning with 'p' and using the '-e' tag to denote a send, receive, queue or drop packet event. Also, this trace uses the '-z' tag to denote packet size.

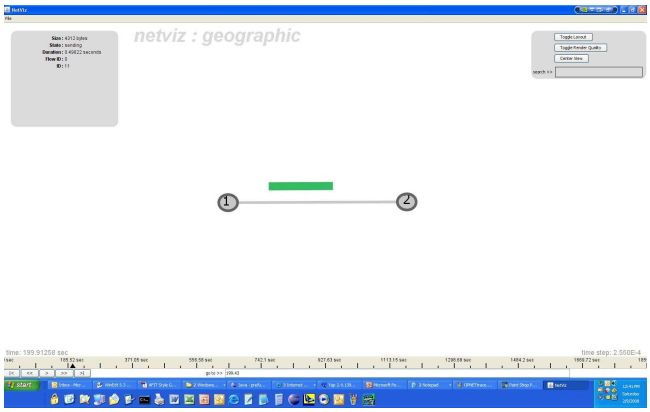


Figure 4.2: Framework visualization of OPNET simulation

needed to parse the OPNET trace file. Figure 4.2 shows the simple OPNET trace using this network visualization framework.

This framework extended `TraceLine` for two different network event line traces. `NamLine` extends `TraceLine` to parse network event lines from NS-2 trace files. `OpNetLine` extends `TraceLine` to parse network events recorded from a scenario run in OPNET. Listing IV.1 below shows the conditional logic used to determine which subclass of `TraceLine` will be used based the trace file extension.

Listing 4.0:

```
if(fileExtension.equals("nam"))
    nextLine = new NamLine(fileIn.readLine());
else
    nextLine = new OpNetLine(fileIn.readLine());
```

The `NextLine` object is of type `TraceLine` and according to the conditional logic is instantiated as either a `NamLine` or a `OpNetLine` based on whether the trace file is Nam or OPNET. The conditional logic in Listing IV.1 can be extending as needed to accommodate additional trace file formats. Once the correct `TraceLine` subclass is instantiated the developer can add specific parsing logic as needed by the new subclass in order to parse the simulator trace line.

This design uses `TraceLine` to define core methods used to obtain information from the network event trace lines, but allows `NamLine` and `OpNetLine` subclasses to supplement and override methods as necessary . Figure 4.3 illustrates methods overriden by `OpNetLine` to retrieve specific information the logged OPNET network events.

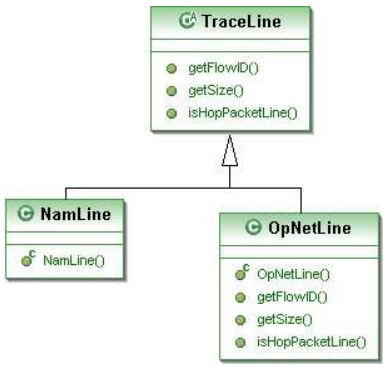


Figure 4.3: `NamLine` and `OpNetLine` subclass `TraceLine`. `OpNetLine` adds functionality to `TraceLine` with new methods and method overrides–allows `TraceLine` to handle network events in OPNET trace file.

The file parser built for this network visualization framework creates an excellent foundation for future research and collaboration. The capability brings network simulator research one step closer to comparing executed network simulator scenarios in a common visualization environment. A comparison that would provide better understanding on how simulators differ and how those differences can effect network event simulation. Additionally, network simulator performance could be seamlessly analyzed and compared from one simulator to another.

4.2 Multi-objective Dynamic Network Topology Layout

This research designed and implemented a network visualization framework to assist network observation and analysis. When implementing a network visualization framework a major concern is how to visualize the network topology. An obvious answer to this question is to arrange network nodes and links as close to their physical arrangement as possible. However, sometimes a physical layout does not provide suffi-

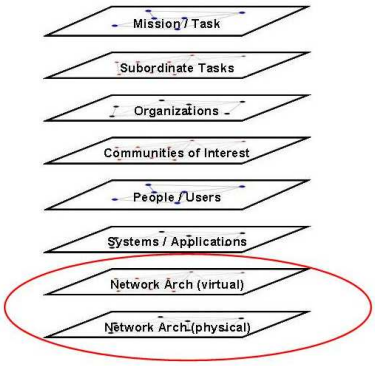


Figure 4.4: Layers of cyberspace situational awareness: This framework provides network architecture (physical and virtual) layers

cient information about how the network is working or the network protocol/problem being studied. Nodes can appear on top of each other and packets can quickly become congested and blur together. For these reasons, a physical network layout is not always best for analyzing and observing network events.

This framework provides the capability to easily alter visualization of network topology and network events. This capability employed on a real network would greatly increases network situational awareness. Network situational awareness is a big part of cyberspace situational awareness and the Center for Cyberspace Research at the Air Force Institute of Technology highlighted cyberspace situational awareness as an important area for future research [35]. Additionally, the center defines eight layers of interest regarding cyberspace situational awareness including physical network architecture and virtual network architecture (see Figure 4.4). This research seeks to advance cyberspace situational awareness up the hierarchy in Figure 4.4 with a framework designed to allow visualization customization for network topology and network events. Furthermore, this research presents two network simulator scenarios to show how altering network visualization of topology and network events increases cyberspace situational awareness.

In chapter III this research described specific layouts for nodes and packets. However, these layouts did not extend the ***prefuse*** layout class. These layouts instead

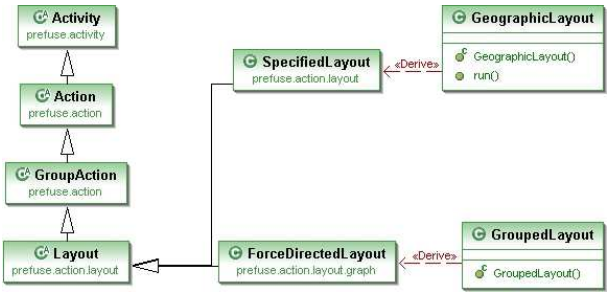


Figure 4.5: `GeographicLayout` and `GroupedLayout` class hierarchy. The `GeographicLayout` and `GroupedLayout` classes extend `Layout` and `Activity` to create customized visualization animation

provided update methods called during the 'netviz_anmiation' thread. This research also defines two different layouts which extend the ***prefuse*** `Layout` class. These two layouts create a physical and virtual view of the network visualization and contribute to two layers of cyberspace situational awareness in Figure 4.4.

4.2.1 Physical and Virtual Network Layout Design. ***Prefuse*** provides an excellent toolkit architecture for supporting different user-defined visualization layouts. This framework leverages the ***prefuse*** toolkit architecture to define two different network topology layouts. First, a physical layout which draws networks of nodes on a grid using the x,y coordinates found in trace file node event lines. Second, a virtual grouped layout which organizes nodes together based on links that exists between the nodes. Nodes that share higher bandwidth links are pulled closer together and nodes that share lower bandwidth links appear farther apart. These two layouts appear in the framework implementation as `GeographicLayout` and `GroupedLayout` respectively. Figure 4.5 shows the class hierarchy of these two classes. Because `GroupedLayout` inherits from ***prefuse*** `ForceDirectedLayout`, nodes without links continue to move farther and farther apart. The class hierarchy in Figure 4.5 also illustrates how any subclass of `Layout` is also a subclass of `Activity`. This is important because as an `Activity` object `Layout` objects are added to the ***prefuse*** `ActivityManager` and used to to create visualization animation. Therefore, by using the ***prefuse*** class hierarchy design, new `Layout` subclasses automatically effect

visualization animation. This design gives developers a simple way to change how network events are animated. The next two sections highlight specific network simulator scenarios that utilize `GroupedLayout` to visually highlight specific network events.

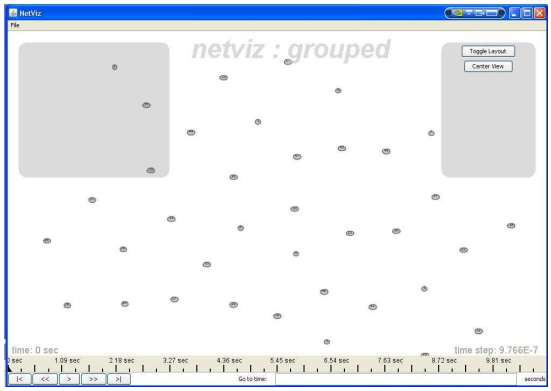
4.2.2 Virtual Network Layout Example I: Wireless Network Broadcast. Effectively visualizing network events requires the visualization logic to create a picture where users can quickly and accurately understand what is happening in the network. Wireless networks is a difficult venue fill this requirement. This is because wireless packets are often broadcast to multiple nodes and without link lines highlighting a packets path it is difficult to know a packets final destination. Tracing wireless packet routes becomes even more difficult as more and more wireless nodes broadcast and the areas around nodes becomes more and more congested with packet traffic.

This framework overcomes these challenges by using `GroupedLayout`. Using `GroupedLayout` a network of many nodes groups together based on node communication. Nodes that broadcast to one another group together to make packet destinations obvious. Figure 4.6 shows a wireless trace file excerpt with one hop event followed by six receive events, each at different nodes. Tracking these packets could be dif-

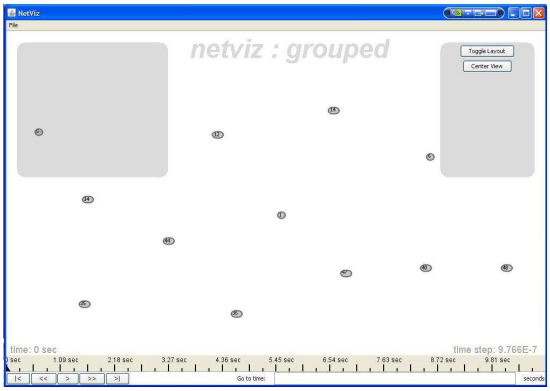
```
h -t 0.000188154 -s 1 -d -1 -p LAR -e 82 -c 2 -a 0 -i 3 -k MAC
r -t 0.000516193 -s 1 -d 14 -p LAR -e 30 -c 2 -a 0 -i 3 -k MAC
r -t 0.000516215 -s 1 -d 6 -p LAR -e 30 -c 2 -a 0 -i 3 -k MAC
r -t 0.000516222 -s 1 -d 47 -p LAR -e 30 -c 2 -a 0 -i 3 -k MAC
r -t 0.000516274 -s 1 -d 40 -p LAR -e 30 -c 2 -a 0 -i 3 -k MAC
r -t 0.000516282 -s 1 -d 36 -p LAR -e 30 -c 2 -a 0 -i 3 -k MAC
r -t 0.000516283 -s 1 -d 12 -p LAR -e 30 -c 2 -a 0 -i 3 -k MAC
```

Figure 4.6: NS-2 trace directing wireless broadcast from node 1 to nodes: 14, 6, 47, 40, 36, 12. As shown in Figure 4.7

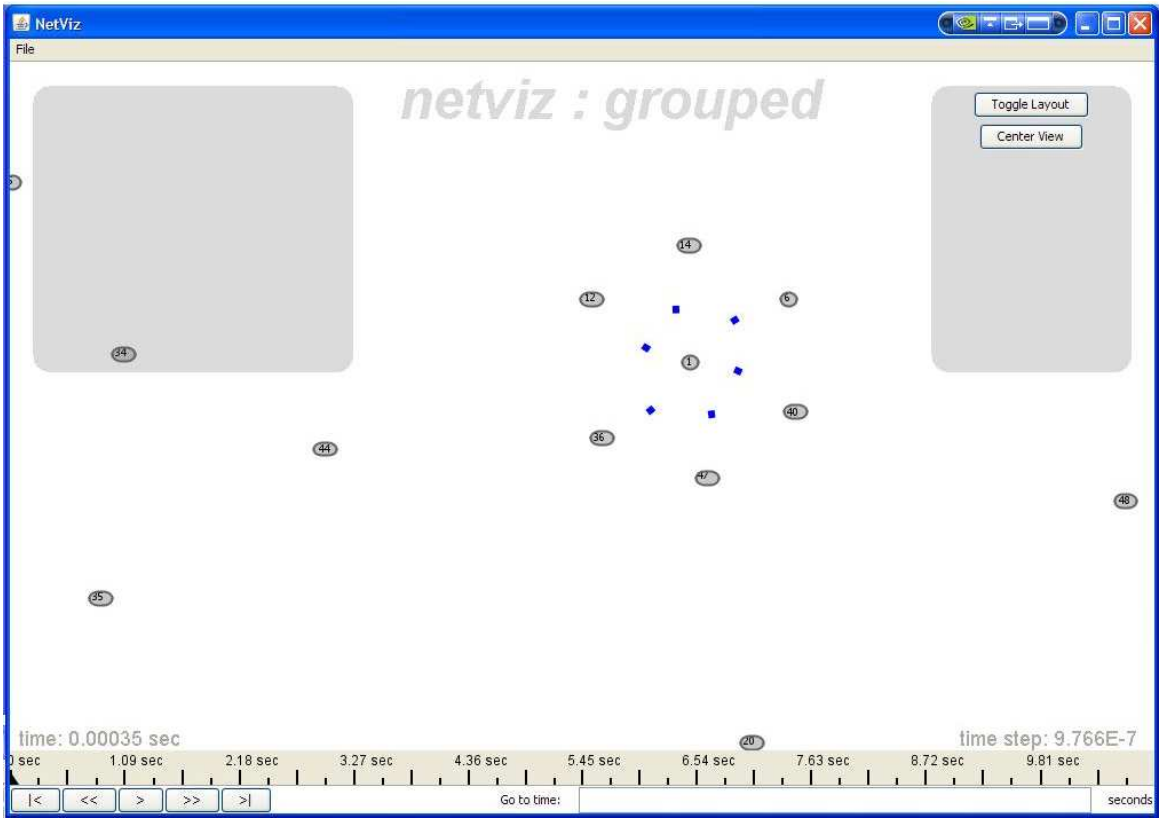
ficult in a physical network layout, especially if the nodes were far apart or packet traffic was high. However, Figure 4.7 illustrates how this visualization framework's `GroupedLayout` emphasizes wireless packet destinations making them easier to track. Also, by quickly highlighting packet destinations additional network conditions may become apparent such as: defective nodes, compromised nodes, and nodes that are obstructed from sent packet transmissions.



(a) Collection of 50 wireless nodes visualized using force-directed layout prior to any packet broadcasts at time zero



(b) Identical network at the same time zoomed in using ***prefuse*** toolkit zoom feature

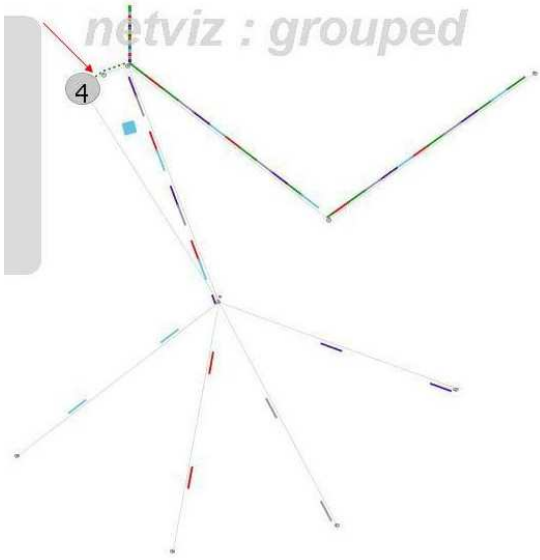


(c) Packet broadcast from node 1: grouped layout causes nodes receiving packets to move closer to node 1

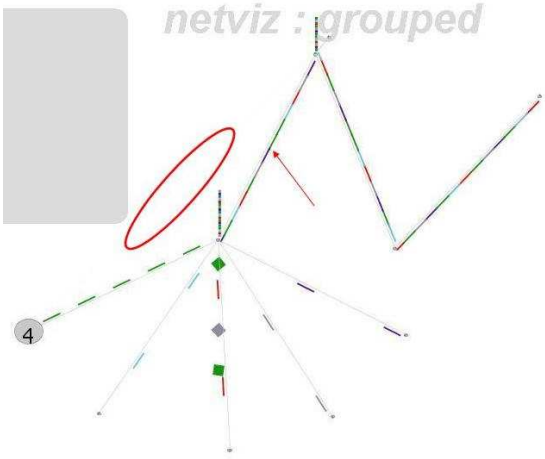
Figure 4.7: Wireless packet broadcast using combination of force-directed and grouped layout

4.2.3 Virtual Network Layout Example II: Wired Network Link Break. The ***prefuse*** toolkit `GroupedLayout` object also effectively highlights other network events. The `GroupedLayout` object defines network nodes that repel one another and network links that pull nodes together. This scenario creates a network layout animation that highlights network link breaks by radically changing network topology. This behavior assists users by more effectively drawing attention to a broken link. Figure 4.8 illustrates this behavior by highlighting specific times during the network event visualization scenario. 4.8(a) shows the network visualization at time 1.02 seconds. At this point all network links are up, however, the red arrow points to the link between 4 and 5 which is about to change from up status to down status. 4.8(b) shows that node 4 has significantly changed position in the network as a result of the down link between 4 and 5. The circle in 4.8(b) indicates that the link between 4 and 5 will soon be brought back up and the red arrow highlights the link between 3 and 6 which will go down. 4.8(c), again, highlights the radical changes in appearance to the network as link status changes. The circle in 4.8(c) indicates that the link between 3 and 6 will soon change to up status. 4.8(d) highlights the network with all links up and appears the same as the original network in 4.8(a).

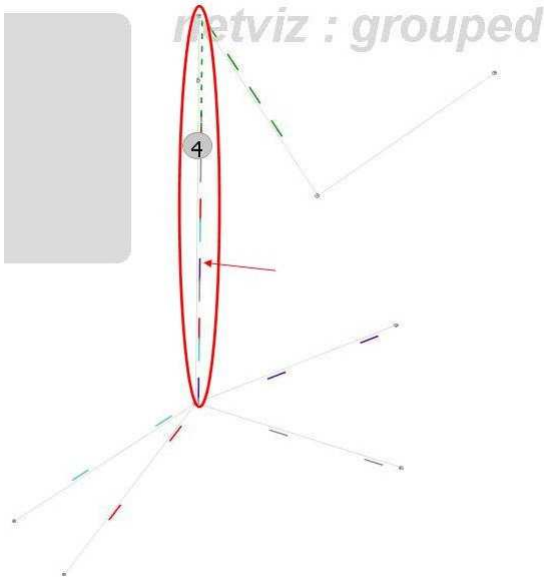
4.2.4 Discussion. The ***prefuse*** toolkit's design allows developers to define specific `Layout` objects to customize how a visualization appears on screen. This capability is a crucial part of creating an effective network event visualization because it combines the components of physical network architecture with virtual network architecture to enhance cyberspace situational awareness. This capability allows visualization's to highlight specific network events of importance to network visualization users. In subsection 4.2.2 and subsection 4.2.3 two examples of extending `Layout` to highlight network events were shown. These examples used `GroupedLayout` to help users trace wireless packets and track link status. These two examples establish the effectiveness of ***prefuse*** toolkit `Layout` objects.



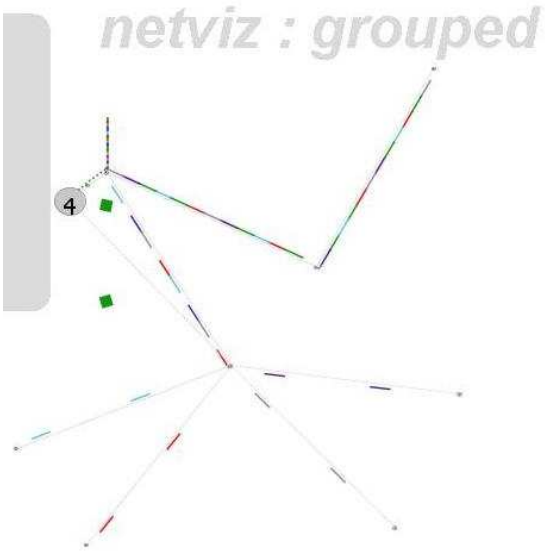
(a) Wired network topology–arrows point out network links that will go down



(b) Altered network topology–arrow points to link that will go down and oval shows links that will go up



(c) New network topology–arrow points to link currently carrying packets which will go down, oval show link currently not visible that will go up



(d) Original network topology restored

Figure 4.8: Wired Network showing network topology animation in response link status changes from up to down

4.3 Analysis-based User Interface

Building an effective network visualization framework requires a user interface that gives users the ability to alter specific visualization characteristics. The framework created through this research uses the ***prefuse*** visualization toolkit to provide many commonly used visualization capabilities. The ***prefuse*** design not only contains many commonly used visualization capabilities, but also allows for easy extension of existing ***prefuse*** classes into user defined classes. Some of the ***prefuse*** visualization toolkit capabilities include: panning, zooming, drag control, and focus control. By capturing these ***prefuse*** capabilities in a network event visualization framework this research contributes a new approach for developing network event visualization software.

Figure 4.9 shows the ***prefuse*** visualization toolkit design for handling various visualization controls as described previously (see `PanControl`, `AbstractZoomControl`, `DragControl`, and `FocusControl`). One of the major benefits of the ***prefuse*** visualization toolkit is that when the toolkit design is understood it is easy to add additional functionality. An example of this is shown in Figure 4.9 by extending `FocusControl` with `SuperFocusControl`. This action overrides `itemKeyPressed`, `itemClicked`, and `mouseClicked` methods to redefine how the visualization assigns focus when the user clicks on the visualization background. `SuperFocusControl` changes visualization focus to nothing when the user clicks on the background; a more intuitive result then keeping the focus the same. Extending ***prefuse*** base classes, like `FocusControl`, and overriding certain methods demonstrates an elegent way to enhance and customize visualization behavior.

Other helpful user interface capabilities included in this visualization framework are: fast-forward/rewind, pause, jump slider, and user-input jump. Again, these controls assist the user during analysis of network events during the visualization. Many of these features are included with Nam, however, the user-input jump is a new feature not included in Nam. Figure 4.10 illustrates these different user interfaces.

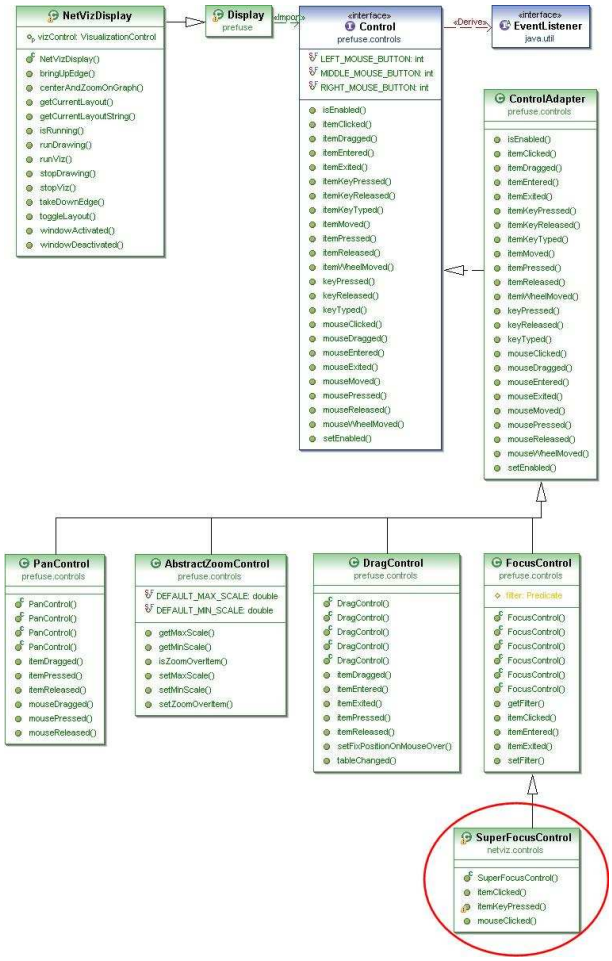


Figure 4.9: ***Prefuse*** visualization architecture for handling various visualization control capabilities. `SuperFocusControl` is a new visualization control added by this framework to custimize how focus changes when users click on the visualization background.

4.4 Testing and Validating the Visualization Framework

The previous examples of wireless node broadcasts and a disabled network links demonstrate some of this frameworks features. The two network visualization examples illustrate the visualizations capability to show wireless and wired topologies, wired packet traffic, wireless broadcasts, disabled links, and dropped packets. This section further verifies this framework's capability to visualize network events from a trace file by showing: packet movement (including queueing) in different network topologies and wireless node movement.

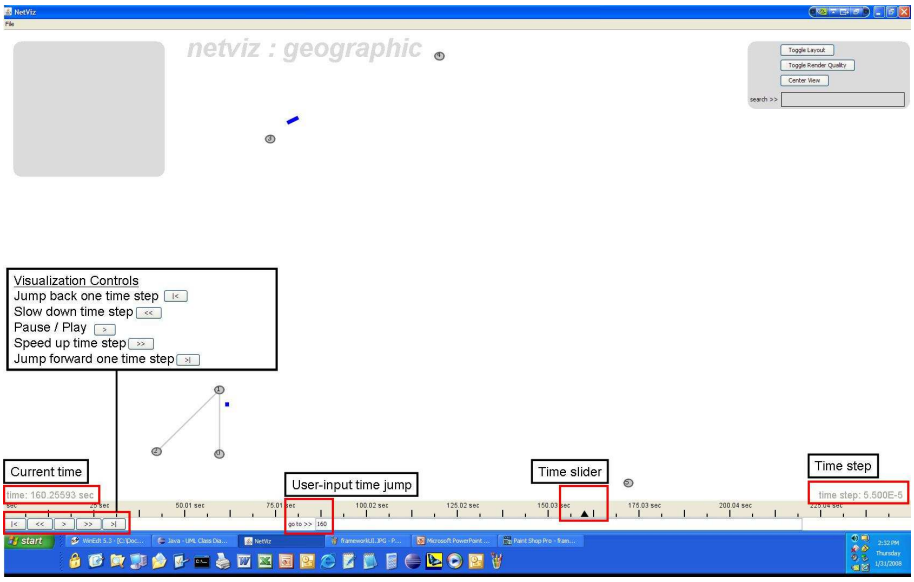


Figure 4.10: Network Visualization framework user-interface with visualization controls highlighted

4.4.1 Wired packet queueing. Figure 4.11 and Figure 4.12 illustrate distinct capabilities of this visualization framework. 4.11(a) shows extracted lines from a Nam trace accounting for packet sends and packet queues. 4.11(b) shows extracted lines from the same Nam trace accounting for packet dequeues. The dequeues in 4.11(b) are significant because in the Figure 4.12 screenshots these dequeues have not yet occurred. Figure 4.12 shows Nam and this visualization framework paused at the same time during their visualizations. At this point in time all queued packets in 4.11(b) are visible in the two screenshots and appear as they should in the node queues. Therefore, Figure 4.12 verifies wired packet queueing for this framework because it matches the Nam visualization. Additionally, the packet traffic in Figure 4.12 is identical between Nam and this framework which verifies wired packet transmissions.

4.4.2 Wireless node movement. Figure 4.7 showed a wireless network topology using the force-directed layout. However, this visualization framework can also show the same network topology using node x,y coordinates specified in the trace file. The frameowork layout that provides this capability is `GeographicLayout` (see Figure 4.5. Combining the `GeographicLayout` with the node mobility data struc-

Packet hops and enqueues

```
h -t 1.03 -s 1 -d 2 -p cbr -e 500 -c 2 -i 112 -a 2 -x {1.0 3.0 -1 ------- null}
h -t 1.03 -s 0 -d 2 -p cbr -e 500 -c 1 -i 113 -a 1 -x {0.0 3.0 -1 ------- null}
h -t 1.035 -s 1 -d 2 -p cbr -e 500 -c 2 -i 114 -a 2 -x {1.0 3.0 -1 ------- null}
+ -t 1.049 -s 2 -d 3 -p cbr -e 500 -c 1 -i 115 -a 1 -x {0.0 3.0 107 ------- null}
+ -t 1.054 -s 2 -d 3 -p cbr -e 500 -c 2 -i 116 -a 2 -x {1.0 3.0 8 ------- null}
+ -t 1.054 -s 2 -d 3 -p cbr -e 500 -c 1 -i 117 -a 1 -x {0.0 3.0 108 ------- null}
+ -t 1.059 -s 2 -d 3 -p cbr -e 500 -c 2 -i 118 -a 2 -x {1.0 3.0 9 ------- null}
+ -t 1.059 -s 2 -d 3 -p cbr -e 500 -c 1 -i 119 -a 1 -x {0.0 3.0 109 ------- null}
h -t 1.06 -s 1 -d 2 -p cbr -e 500 -c 2 -i 124 -a 2 -x {1.0 3.0 -1 ------- null}
h -t 1.06 -s 0 -d 2 -p cbr -e 500 -c 1 -i 125 -a 1 -x {0.0 3.0 -1 ------- null}
+ -t 1.064 -s 2 -d 3 -p cbr -e 500 -c 2 -i 120 -a 2 -x {1.0 3.0 10 ------- null}
+ -t 1.064 -s 2 -d 3 -p cbr -e 500 -c 1 -i 121 -a 1 -x {0.0 3.0 110 ------- null}
h -t 1.065 -s 1 -d 2 -p cbr -e 500 -c 2 -i 126 -a 2 -x {1.0 3.0 -1 ------- null}
h -t 1.065 -s 0 -d 2 -p cbr -e 500 -c 1 -i 127 -a 1 -x {0.0 3.0 -1 ------- null
+ -t 1.069 -s 2 -d 3 -p cbr -e 500 -c 2 -i 122 -a 2 -x {1.0 3.0 11 ------- null}
+ -t 1.069 -s 2 -d 3 -p cbr -e 500 -c 1 -i 123 -a 1 -x {0.0 3.0 111 ------- null}
h -t 1.07 -s 1 -d 2 -p cbr -e 500 -c 2 -i 128 -a 2 -x {1.0 3.0 -1 ------- null}
h -t 1.07 -s 0 -d 2 -p cbr -e 500 -c 1 -i 129 -a 1 -x {0.0 3.0 -1 ------- null}
```

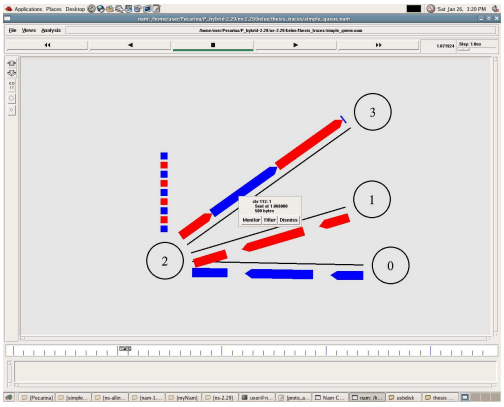
(a) Nam trace file lines for packet hops and enqueues accounting for packets seen in 4.12(a) and 4.12(b)

Packet dequeues that have not yet occured

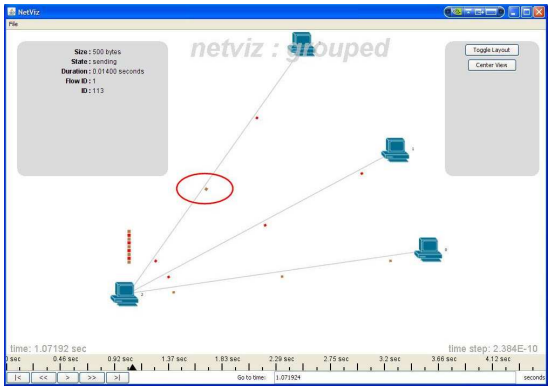
```
- -t 1.074 -s 2 -d 3 -p cbr -e 500 -c 1 -i 115 -a 1 -x {0.0 3.0 107 ------- null}
- -t 1.078 -s 2 -d 3 -p cbr -e 500 -c 2 -i 116 -a 2 -x {1.0 3.0 8 ------- null}
- -t 1.082 -s 2 -d 3 -p cbr -e 500 -c 1 -i 117 -a 1 -x {0.0 3.0 108 ------- null}
- -t 1.086 -s 2 -d 3 -p cbr -e 500 -c 2 -i 118 -a 2 -x {1.0 3.0 9 ------- null}
- -t 1.09 -s 2 -d 3 -p cbr -e 500 -c 1 -i 119 -a 1 -x {0.0 3.0 109 ------- null}
- -t 1.094 -s 2 -d 3 -p cbr -e 500 -c 2 -i 120 -a 2 -x {1.0 3.0 10 ------- null}
- -t 1.098 -s 2 -d 3 -p cbr -e 500 -c 1 -i 121 -a 1 -x {0.0 3.0 110 ------- null}
- -t 1.102 -s 2 -d 3 -p cbr -e 500 -c 2 -i 122 -a 2 -x {1.0 3.0 11 ------- null}
- -t 1.106 -s 2 -d 3 -p cbr -e 500 -c 1 -i 123 -a 1 -x {0.0 3.0 111 ------- null}
```

(b) NS-2 trace file lines for packet dequeues accounting for queued packets seen in 4.12(a) and 4.12(b)

Figure 4.11: NS-2 trace file lines accounting for Figure 4.12



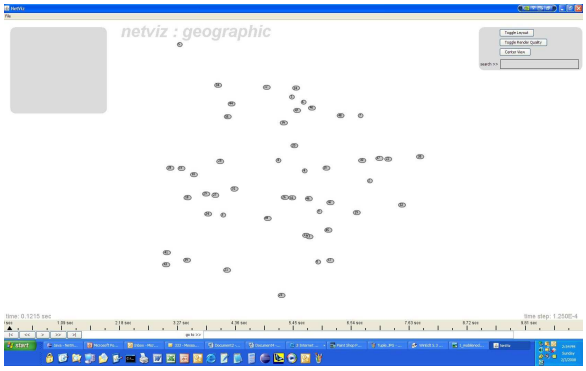
(a) Nam screenshot showing wired packet animation and queueing



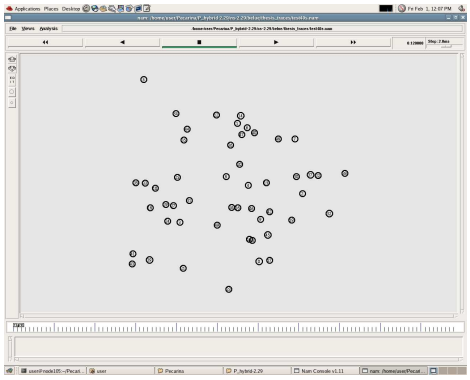
(b) Network Visualization screenshot showing wired packet animation and queueing

Figure 4.12: Nam and this framework's visualization of wired packet traffic with both visualizations paused at the same time

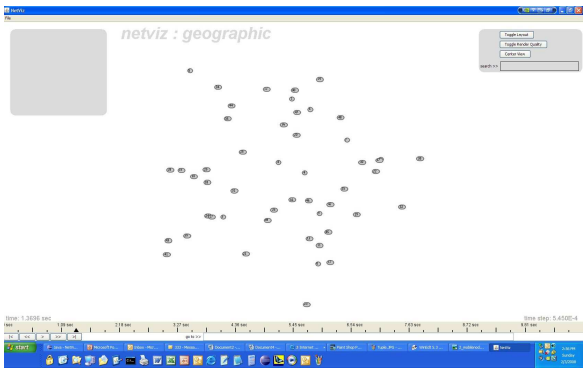
ture discussed in chapter III (see Figure 3.11) this framework creates node movement animation. This section establishes node movement animation accuracy for the visualization framework by tracing node movement during network event visualization. Figure 4.13 shows this framework and Nam animating the same trace file with screenshots taken from both visualizations at the same time.



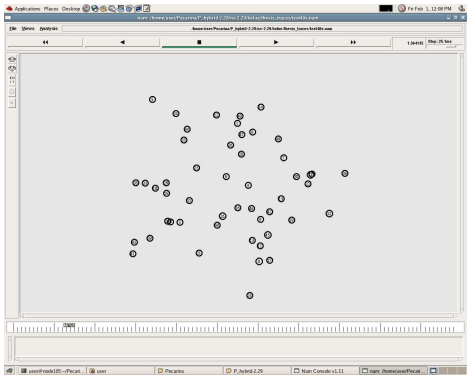
(a) Framework node movement at time = .1215



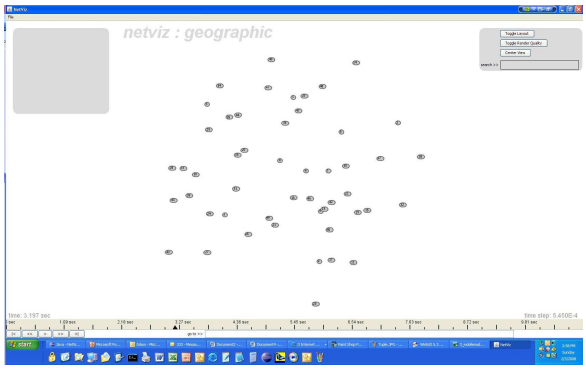
(b) Nam node movement at time = .1200



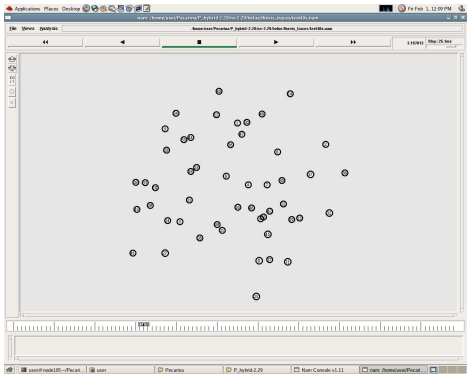
(c) Framework node movement at time = 1.3696



(d) Nam node movement at time = 1.364135

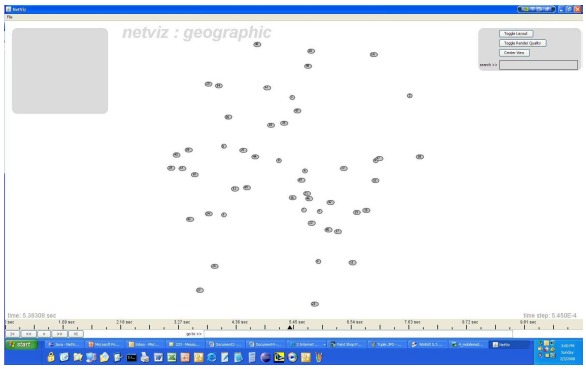


(e) Framework node movement at time = 3.197

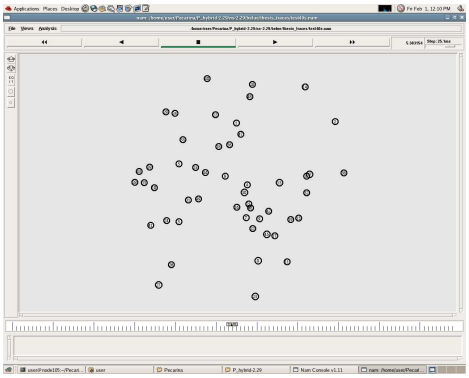


(f) Nam node movement at time = 3.197813

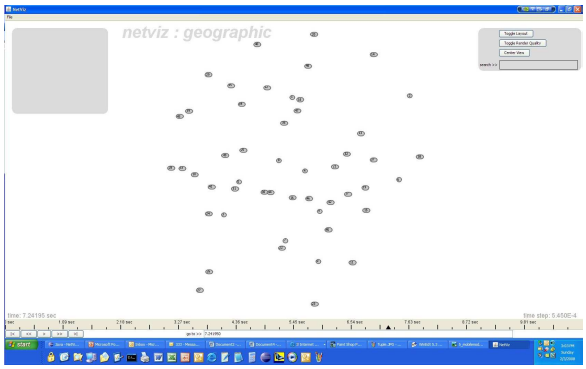
Figure 4.13: This visualization framework node movement animation compared to Nam



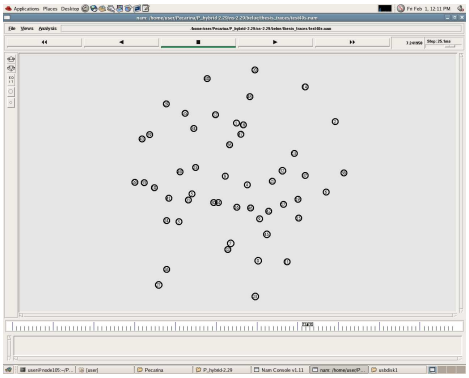
(a) Framework node movement at time = 5.38308



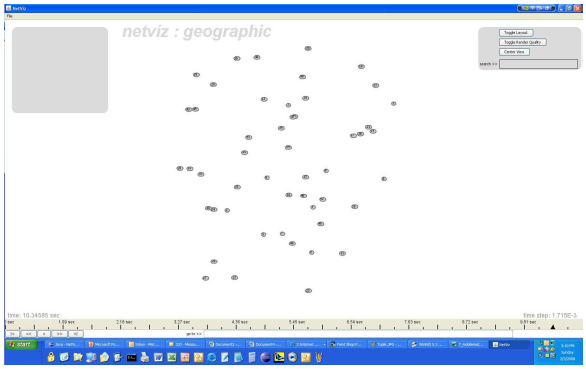
(b) Nam node movement at time = 5.383154



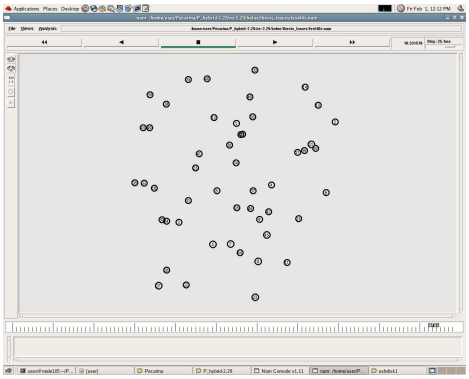
(c) Framework node movement at time = 7.24195



(d) Nam node movement at time = 7.241950



(e) Framework node movement at time = 10.34585



(f) Nam node movement at time = 10.331570

Figure 4.14: This visualization framework node movement animation compared to Nam (cont)

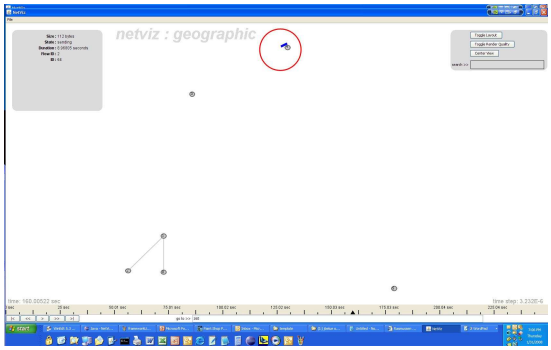
```
+ -t 160.004330839 -s 3 -d 4 -p tcp -e 112 -c 2 -a 0 -i 64 -k MAC
- -t 160.004330839 -s 3 -d 4 -p tcp -e 112 -c 2 -a 0 -i 64 -k MAC
h -t 160.004330839 -s 3 -d 4 -p tcp -e 112 -c 2 -a 0 -i 64 -k MAC
r -t 160.005227645 -s 4 -d 4 -p tcp -e 60 -c 2 -a 0 -i 64 -k MAC
+ -t 160.009627335 -s 4 -d 2 -p tcp -e 112 -c 2 -a 0 -i 64 -k MAC
- -t 160.009627335 -s 4 -d 2 -p tcp -e 112 -c 2 -a 0 -i 64 -k MAC
h -t 160.009627335 -s 4 -d 2 -p tcp -e 112 -c 2 -a 0 -i 64 -k MAC
r -t 160.010524116 -s 2 -d 2 -p tcp -e 60 -c 2 -a 0 -i 64 -k MAC
```

Figure 4.15: Wireless packet trace for wireless packet travelling from node 3 to 4 and finally node 2

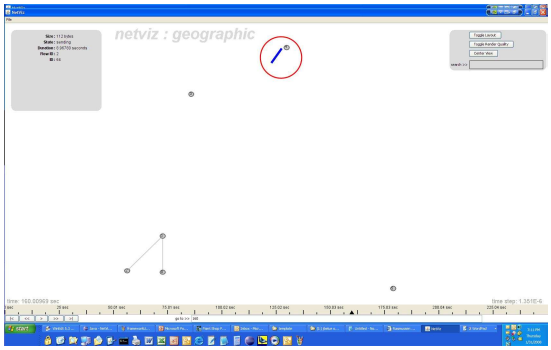
4.4.3 Wireless and wired network topology packet trace. Visual inspection of wireless traffic reveals an interesting differences between this visualization framework and Nam. Figure 4.15 defines network packet traffic for packet ID 64 originating at node 3. Packet 64 is first sent to node 4 and then from node 4 it is sent to node 2. Figure 4.16 shows these two packet transmissions visualized by this framework. Figure 4.16(a) shows the first wireless transmission for packet 64 from node 3 to node 4. Figure 4.16(b) shows the second wireless transmission from node 4 to node 2. The visualization screenshots in Figure 4.16 verify that this framework accurately shows wireless packet broadcasts for packet 64. However, running the same trace file in Nam highlights inaccuracies in the visualization. Figure 4.17(a) shows the wireless packet moving between nodes 3 and 4 and Figure 4.17(b) shows the packet moving between nodes 4 and 2. Figure 4.17(b) clearly shows a packet in route to node 4, however, Figure 4.17(b) also shows that the same packet is actually broadcast from node 4 before the enroute packet from node 3 actually arrives. Figure 4.17 points out a wireless packet visualization error with Nam wireless packet animation. Packet 64 is not correctly visualized and does not accurately reflect the behavior defined by the the trace shown in Figure 4.15.

4.5 Discussion

The examples in this section illustrate the capabilities of this visualization framework. The framework is extensible and allows multiple trace file formats to be parsed and visualized. This capability will invite new levels of analysis across different network simulators–providing a common visualization framework to analyze differences

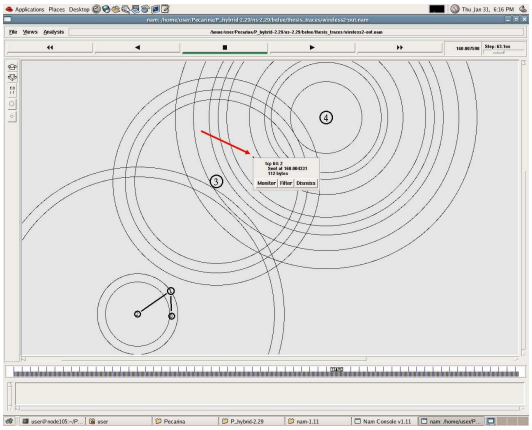


(a) Packet 64 transmission from node 3 and received by node 4

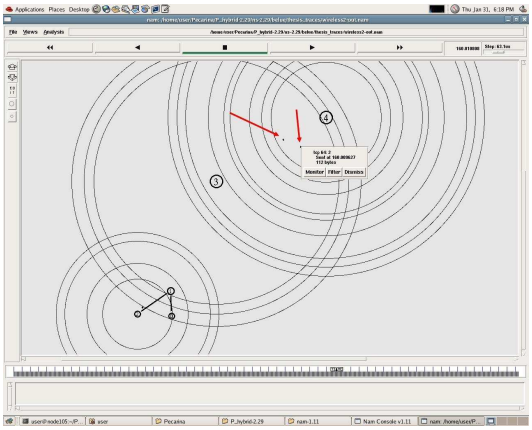


(b) Packet 64 transmission from node 4 to node 2

Figure 4.16: This network visualization framework's animation of wireless packet moving from wireless node to wired network topology



(a) Nam screenshot showing packet animation from node 3 to node 4



(b) Nam packet animation showing packet 64 transmitted to node 2 from node 4 before packet 64 is received by node 4

Figure 4.17: Nam's network animation of wireless packet moving from wireless node to wired network topology

in simulators. Also the new framework gives users enhanced user-interface controls which give user precise visualization control. The extensible network topology layouts give users the ability to define how network events are visualized. This ability puts users in command of what network event information is relevant and allows them to remove irrelevant information from the visualization through new ***prefuse*** `Layout` development. The visualization framework steps forward with these new capabilities and contributes to future network research and analysis.

V. Contributions and Future Work

This research claims three main contributions which advance network visualization. First, a robust trace file parser design extensible to accept multiple trace formats. Second, a robust network visualization layout design which includes several different layouts and is also extensible to include custom user-defined layouts. Third, precise visualization timing controls to quickly show network status and events at a specific time. Through these contributions this research has produced a network visualization framework that is capable of parsing network simulator trace files to produce a network event visualization. The framework will assist future users as they analyze network performance and evaluate network protocols and routing algorithms on both simulators and real networks. These contributions will also enhance cyberspace situational awareness which continues to grow into a bigger and bigger part of Air Force operations. Future work on this framework will enhance file parsing, visualization layouts, and allow real-time interaction with network simulators.

5.1 Contributions

5.1.1 Robust Framework Trace Parser. This research showed that the parser designed in chapter III and implemented in this framework is extensible to accept different trace file formats. As illustrated in chapter IV this capability highlights how the framework was extended to parse and visualize a trace from OPNET. This capability gives network simulator users a universal visualization platform for simulator traces provided the trace conforms to the specifications outlined in chapter IV. In addition to providing a robust parser this framework also highlighted errors in Nam (see chapter IV Figure 4.17). By correctly parsing network event trace lines this framework accurately animates wireless network packet events. Multi-trace acceptance and accurate wireless packet event animation contribute to this framework's advancement of network visualization.

5.1.2 Extensible Visualization Layout. In subsection 4.2.2 this research presented and example of using `GroupedLayout` to highlight network link breaks.

This section presents a possible real-world scenario to emphasize the possible impact a network link going down. Additionally, this section highlights how by using this framework with the `GroupLayout` commanders can receive early warning of upcoming information loss.

Figure 5.1 illustrates a possible real-world scenario for monitoring a military network. Figure 5.1 shows visualization screenshots that illustrate what is happening in the network. This network scenario focuses on the UAV node to highlight framework capabilities. Figure 5.1(a) shows the initial network with all links up and the UAV communication with the satellite. In Figure 5.1(b) the link between the satellite and the UAV goes down and the UAV has to re-route traffic through the aircraft carrier. Figure 5.1(c) shows the result of this UAV traffic re-routing as the queue on the aircraft carrier begins to spike from the increased network traffic.

This scenario illustrates the power of this visualization framework. First, the link break dramatically altered the network topology and aligned the UAV more with the carrier than with the satellite. Second, the visualization shows the aircraft carriers queue spike indicating that the traffic load is too great and eventually information will be lost. In a real-world scenario these two factors would alert network analysts to inform commanders of the potential information loss and evasive action could be taken. This possible scenario shows how this network visualization framework provides vital network situational awareness.

5.1.3 User Interface. This framework employs a precise user-interface to assist users while navigating through a network visualization. Key to efficient analysis are precise timing controls. These controls allow the user to quickly jump to a specific time without having to use fast forward or rewind features which commonly result and overshooting the desired time period. Additionally node statistics are given when a user clicks on a desired node. Figure 5.2 illustrates this feature by showing packet receives, drops, and receive/drop percentages. These features give the user the

control and information needed to perform network performance analysis at a higher level than other network visualizations.

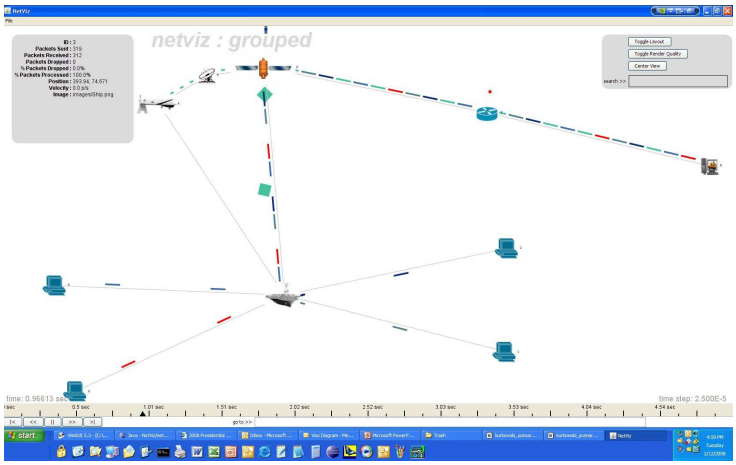
5.2 Future Work

The three major contributions of this research already show promise for improvement which is exciting because it validates the importance of the robust design used to create the contributions. Future framework iterations will build on this robust design. Parser enhancement will better organize code to facilitate robust creation of trace file parsers. Layout enhancements will better visualize large wired network topologies. Finally, using the methodology discussed in chapter III and the OPNET toolkit developed by Mark Coyne [6] this visualization will interact real-time with the OPNET simulator.

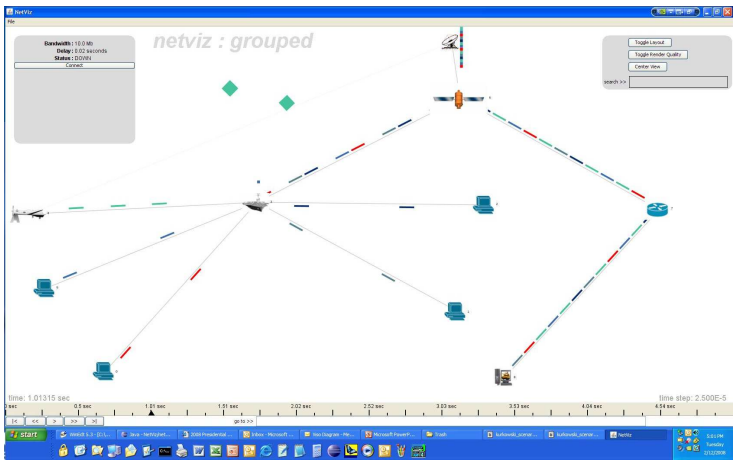
5.2.1 Parser Enhancements. Additional research is needed for using network simulator trace files in a network visualization. This research used 16 different traces to examine network visualization performance. One of these traces was from OPNET, but the rest were from NS-2. The visualization could be greatly benefited by examining more traces from different simulators to establish the framework as a robust network visualization framework.

Currently framework implementation creates `TraceLine` subclasses using a chain of conditional logic which tests which subclass is needed. A better design would replace this logic with a `TraceLine` factory. The factory would hold all the logic to determine the `TraceLine` subclass needed to parse network events into the ***prefuse*** visualization data structures. Also, by centralizing `TraceLine` subclass creation into a factory developer parser modifications would be more intuitive.

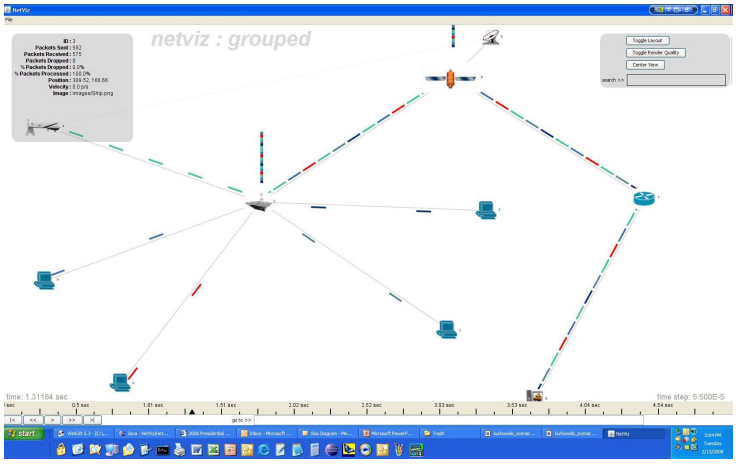
5.2.2 Layout Enhancements. Currently this visualization framework has two separate layouts: `GeographicLayout` and `GroupedLayout`. However, large network topology trace files that do not specify node location and have nodes that are



(a) Real-world network scenario. Here the UAV is communicating via satellite



(b) UAV to satellite link goes down and UAV begins to communicate with the aircraft carrier



(c) As a direct result of increased traffic from the UAV the aircraft carrier's packet queue begins to fill up

Figure 5.1: Potential real-world network scenario

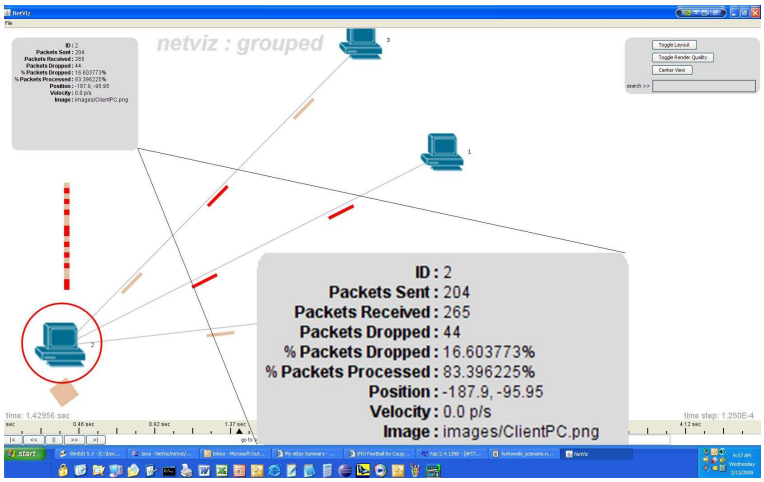


Figure 5.2: Illustration of node statistics kept and displayed by this visualization framework.

intricately connected with one another present a visualization challenge. Figure 5.3 represents such a network. The network represents distribution substations for a power grid and is part of the research conducted by Gregory Roberts, a student at the Air Force Institute of Technology [34]. The networks Gregory Roberts is studying present a visualization challenge because they are large with intricately connected nodes. Even this framework does little to improve visualization by spreading out network nodes with the `GroupedLayout` (see Figure 5.3). This network topology illustrates the need for a new layout which spreads the nodes out using `GroupedLayout`, but then allows users to edit individual node location by dragging nodes to a new position as can be done when using `GeographicLayout`. A possible approach for creating this new layout is to extend `GroupedLayout` and make the new class only move the nodes for a short period of time and then revert back to an anchored layout where nodes only move if they are dragged to new locations.

Because this framework builds on the robust ***prefuse*** visualization toolkit there are many options to enhance network visualization animation and layouts based on user needs. The polylithic design of ***prefuse*** spreads out toolkit functionality across different classes which creates an object-oriented developer friendly implementation environment. Using the ***prefuse*** `Action` class is one way to define specific behavior

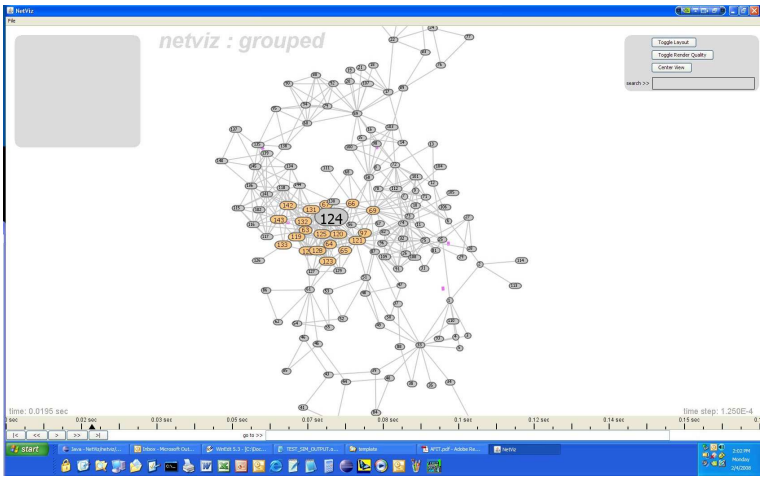


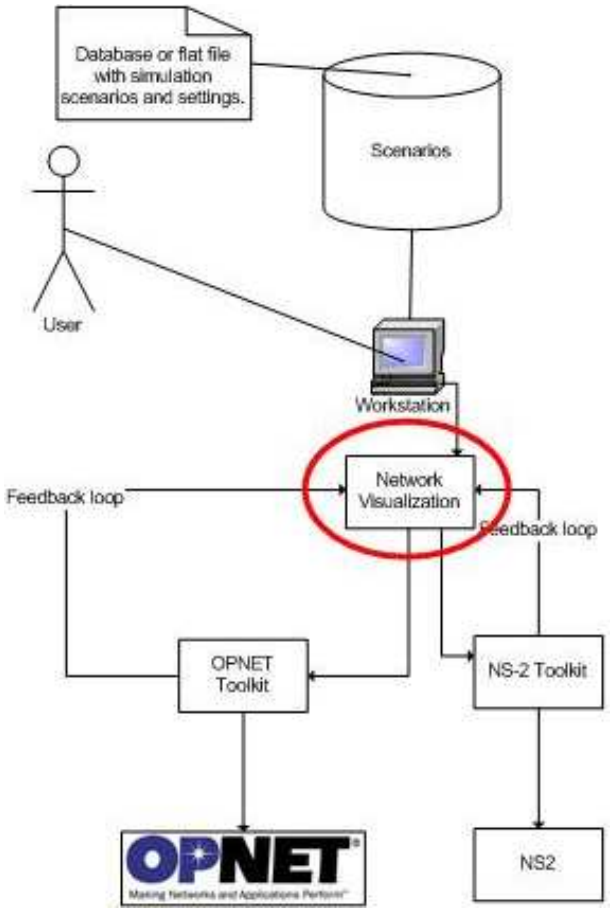
Figure 5.3: Example of ***prefuse*** `Action` objects used to enlarge scrolled over nodes and hight nodes sharing a link

for specific `VisualItem` objects. Figure 5.3 shows two examples of custom `Action` objects defined to alter the appearance of network nodes. One `Action` increases node size when a user scrolls over a node and the other colors neighbor nodes sharing a link with the node. These are only two examples of using the ***prefuse*** `Action` objects to enhance the network visualization. Future development will continue to customize network visualizations using not only the `Action` object but `Layout`, `Control`, and others.

Extending `Layout`, `Action`, and `Control` to enhance visualizations will continue to be a part of any framework that utilizes the ***prefuse*** toolkit. The classes in this toolkit are designed with that very purpose in mind. The examples listed in this section are only some of the changes that will be made to this framework in the future as it continues to grow into a more effective network visualization framework.

5.2.3 Network Simulator Interaction. A major emphasis of network visualization research is to provide a network visualization that can interact with a network simulator to alter network events at runtime. Figure 5.4 shows a design for this interaction. Creating this kind of visualization requires, at least at some level, an understanding of how network simulators work internally. Additionally, the visual-

ization must be equipped to communicate with the network simulator. This research provided a design for this communication, however, the actual implementation remains incomplete. Implementing and testing simulation to visualization interaction remains as an area of future work for this network visualization framework.



[6]

Figure 5.4: Diagram illustrating network simulator interaction goals. Diagram highlights feedback loop between Network Visualization (this framework) and Network simulators via their respective toolkits

5.2.4 Discussion. Because the framework is still in developmental stages, some errors exist in the implementation. One of these problems is out of sync node movement from the trace being visualized. This anomaly is avoidable by not using the jump or slider functionality of the user-interface, however this limits the usefulness of the visualization for analysis of network events.

Despite these anomalies this research provides an effective framework capable of accurately visualizing network events from a network simulator trace file. The parser framework design facilitates parsing trace files with different formats. Additional features of the framework include two different network layouts that can highlight network event trace data in dramatically different ways. The layout design is included in this research to illustrate how future work can create new layout designs to highlight user-specific network trace events. This network visualization contributes these features towards advancing network visualization and network event analysis and provides a solid framework base for future development.

5.3 Conclusion

This research has studied several different existing network visualization software and data visualization toolkits. This study resulted in questions about current network visualization software, data visualization toolkits, and how they could be combined to created a more robust and effective network visualization. As a direct result of these questions this research has created a network visualization framework using the ***prefuse*** toolkit. This framework meets the standards of existing network visualization frameworks in some cases and in others exceeds them. This framework excels with robust network simulator trace filing parsing, extensible network visualization layouts, and precise visualization timing controls. This network visualization framework advances network visualization standards and provides capabilities for future advancement.

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14. ABSTRACT

Visualization of network simulation events or network visualization is an effective and low cost method to evaluate the health and status of a network and analyze network designs, protocols, and network algorithms. This research designed and developed a network event visualization framework using an open source general visualization toolkit. This research achieved three major milestones during the development of this framework: A robust network simulator trace file parser, multiple network visualization layouts–including user-defined layouts, and precise visualization timing controls and integrated display of network statistics.The toolkit design is readily extensible allowing developers to easily expand the framework to meet research-specific visualization goals.

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