Application of Dijkstra Algorithm on OSPF Routing Protocol and its Effect in Modern Networks

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***Abstract*—The Open Shortest Path First (OSPF) protocol is a routing protocol used in the modern age of internet. This protocol is used to define the shortest path of a data stream traversal in order to reach its destination. The need for fast data stream transfer rises as the internet's usage rate rises upon the modern age. In this paper, the author will discuss the implementation of Dijkstra's Algorithm in OSPF Routing Protocol and its effect on modern networks.**

***Keywords*—Dijkstra Algorithm, OSPF, Routing Protocol, Shortest Path First, networking, modern network.**

I. Introduction

The Internet has been growing exponentially for the past decade due to high technological advancements, particularly in networking systems. One of the key factors is also the growing need for the usage of the Internet's resources, such as storage, entertainment, information, and connection. Cisco estimates that the most common traffic in the Internet is video streaming [1], a form of entertainment and information acquirement, and the total traffic of the Internet will reach about 400 exabytes in 2022 [1]. This only strengthens the fact that humanity's need on the Internet will continually growing in the future. Henceforth, the networking technologies must cope for this rapid growth of the Internet usage.

Networks are the most fundamental and essential thing for the Internet's communication systems. It consists of many different aspects, such as hardware (switches and routers are one of the examples) and protocols that controls the interaction on each hardware that makes the communication traffic around the network. Hardwares are connected to each other either by a physical cable or by wireless communication bands to create a network. From these connections, the hardwares can communicate to each other by sending data across the connection. But in complex networks, there are many possible path permutations in order to get to a single destination. Therefore, pathfinding protocols were made to ease the search for the most optimal path to get to a destination. With the optimal traversing path, the delay for data transfer will be minimalized greatly, thus effecting the usage of the Internet.

One of the pathfinding protocols is Open Shortest Path First (OSPF), a protocol that finds the path to destination with minimal cost. It uses Dijkstra Algorithm to find the shortest path to two different nodes in a graph. OSPF was first standardised in 1989 as RFC 1131 [2] designed for autonomous systems like local area networks. Due to its speed on converging networks and avoidance in looping paths, OSPF is widely deployed on networks worldwide.

This paper will discuss the implementation of Dijkstra's Algorithm in OSPF protocol, which used in pathfinding protocol and its effect in modern networks.

II. Dijkstra Algorithm

Dijkstra Algorithm, also known as Shortest Path First Algorithm, is an algorithm that produces the shortest, acyclic path between two nodes in a graph [3]. It was conceived by Edsger Wybe Dijkstra, a Dutch computer scientist in 1956, but Dijkstra published the paper about three years after the discovery [3]. Dijkstra thought about the shortest path problem when working at the Mathematical Center in Amsterdam in 1956 as a programmer to demonstrate the computing power ARMAC computer [4]. To test his solution on the shortest path problem, he devised a slightly simplified transportation map of 64 cities in the Netherlands and apply the algorithm on the map [5]. He published the algorithm in his paper "*A note on two problems in connexion with graphs*".

The shortest path found is based on the metrics given in the graph's edges, thus finding the minimal sum of these metrics upon the path is the goal of Dijkstra Algorithm.

A. Graph and Tree

A graph is a discrete mathematical structure in which every object defined on the graph is related to one another in some configuration.

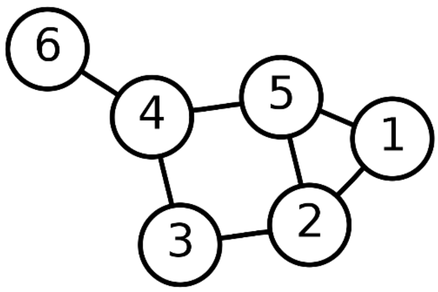


Figure 1 Graph. Source: https://en.wikipedia.org/wiki/Graph_(discrete_mathematics)

The objects in which the mathematical abstraction corresponds in a graph is called vertices. The representation of the connections of the objects, which is the connection between the vertices, is called edges. Degree is the amount of edges adjacent to a vertex. For example, in figure 1, node 6 has a degree of 1, while node 5 has a degree of 3. Two nodes are said to be adjacent if they're connected with the same edge. Node 6 and node 4 are adjacent to each other, but node 6 and node 1 aren't adjacent to each other.

Graph has many variations, but for modelling interactions of objects there are three useful variations of graphs:

1. Undirected Graph, where the edges of the graph don't have any direction in the connection.
2. Directed Graph, where the edges of the graph have direction in the connection. This model usually for a special connection models, such as one-way communication systems.
3. Weighted Graph, where the graph's edges have a number (the weight) is assigned to each edge [6]. Such weights might represent for example costs, lengths or capacities, etc. A weighted graph is represented in figure 3.

Graph has been considered as one of the best mathematical models because of its applicability in almost any problems. It is also widely used as models because of vast amount of "connectivity" problems in the modern world. Not just in mathematics, but also in computer science to model networks, sociology to model social circles and social networks, and in network theory as a fundamental concept.

One very useful variation of a graph is a tree. It is unique enough to make independent theorems based on this variation. A tree T with node n is a graph that's:

- No simple cycles and has n - 1 edges
- Connected and has n - 1 edges, and every subgraph of the graph includes at least one vertex with zero or one incident edges.

A rooted tree is a tree with one of the vertices set as root and all the other vertices is given directions away from the root. Tree has a property that every vertex in a tree can be reached in a unique path from the root [6]. Just like the regular graph's variation, the vertices and edges of a tree can also have weights to model certain problem. A vertex-weighted tree is represented in figure 2. Trees also can be a directed graph. Such trees exist to model the compression algorithm and binary search.

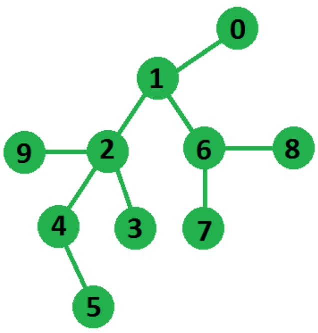


Figure 2 Tree. Source: https://www.cs.cmu.edu/~adamchik/15-121/lectures/Trees/trees.html

B. Dijkstra Algorithm

The Dijkstra Algorithm commonly applies on edge-weighted graphs, because the algorithm is based on models that have costs on each set of edges (paths), and the main goal is to find the path with minimum cost, therefore it is the "shortest" path between two nodes. Because of the acyclic nature of the paths, Dijkstra Algorithm produces shortest path first tree as the paths.

The algorithm is as follows:

1. Mark all nodes unvisited. Create a set of all the unvisited nodes called the unvisited set;
2. Assign to every node a tentative distance value: set it to zero for our initial node and to infinity for all other nodes. Set the initial node as current;
3. For the current node, consider all its unvisited neighbors and calculate their tentative distances (edges' weight) through the current node. Compare the newly calculated tentative distance to the current assigned value and assign the smaller one;
4. When we are done considering all the unvisited neighbors of the current node, mark the current node as visited and remove it from the unvisited set. A visited node will never be checked again;
5. If the destination node has been marked visited (when planning a route between two specific nodes) or if the smallest tentative distance among the nodes in the unvisited set is infinity (when planning a complete traversal; occurs when there is no connection between the initial node and remaining unvisited nodes), then stop. The algorithm has finished. Otherwise, select the unvisited node that is marked with the smallest tentative distance, set it as the new "current node", and go back to step 3.

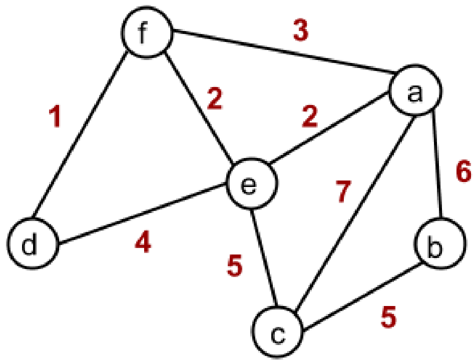


Figure 3 Edge-weighted Graph. Source: https://www.chegg.com/homework-help/questions-and-answers/undirected-weighted-graph-g-given--use-prim-s-algorithm-compute-minimum-spanning-tree-weig-q21203421

For example, consider the graph in figure 3. We will start from node d and find the shortest paths to every node in the graph using Dijkstra Algorithm:

Unvisited	a	b	c	D	e	f
[a, b, c, d, e, f]	∞	∞	∞	0	4	1
[a, b, c, e, f]	1+3	∞	∞		1+2	1
[a, b, c, e]	4	∞	3+5		3	

[a, b, c]	4	4+6	8				
[b, c]		10	8				
[b]		10					
[]	**Finished**						

Table 1 Dijkstra Algorithm Table

The symbol ∞ dictates that the following node is unreachable from the current node. Then according to the table, the shortest path from a to each node is as follows:

- Node d to node a is 4 costs (d – f – a)
- Node d to node b is 10 costs (d – f – a – b)
- Node d to node c is 8 costs (d – f – e – c)
- Node d to node e is 3 costs (d – f – e)
- Node d to node f is 1 cost (d – f)

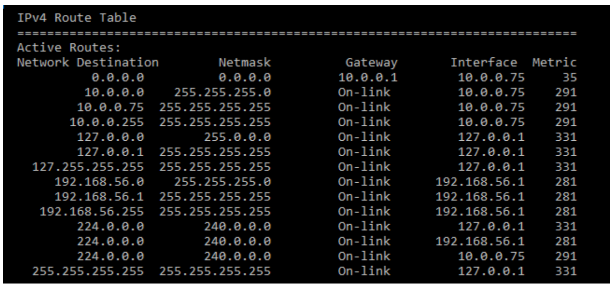
The algorithm applies on both the directed and undirected graph variations, depends on the model.

III. OSPF Protocol Implementation

A. OSPF Protocol

From this section of paper onwards, there are a few terminologies that needs to be understood:

1. Network Bandwidth, or simply bandwidth. Bandwidth is the maximum throughput of a data transfer across a given path.
2. Router. A router is a hardware that forwards data packets between computer networks. It is also directing data traffics inside a network to its destined point.
3. Metrics. A metric is a measurement of a cost of a path, whether it is based on bandwidths, buffer throughputs, etc.
4. Routing Table. It is a table on each router in a network that consists of information base of every routers in a network and the metrics associated with each router. An example of routing table is shown in figure 4.
5. Autonomous System. It is a network system that consists of routing prefixes for the Internet Protocol under one network control or a single administrative entity that supports the internet routing policy.



```
IPv4 Route Table
===========================================================================
Active Routes:
Network Destination        Netmask          Gateway       Interface  Metric
          0.0.0.0          0.0.0.0         10.0.0.1       10.0.0.75     35
         10.0.0.0    255.255.255.0         On-link        10.0.0.75    291
        10.0.0.75  255.255.255.255         On-link        10.0.0.75    291
       10.0.0.255  255.255.255.255         On-link        10.0.0.75    291
        127.0.0.0        255.0.0.0         On-link        127.0.0.1    331
        127.0.0.1  255.255.255.255         On-link        127.0.0.1    331
  127.255.255.255  255.255.255.255         On-link        127.0.0.1    331
     192.168.56.0    255.255.255.0         On-link     192.168.56.1    281
     192.168.56.1  255.255.255.255         On-link     192.168.56.1    281
   192.168.56.255  255.255.255.255         On-link     192.168.56.1    281
        224.0.0.0        240.0.0.0         On-link        127.0.0.1    331
        224.0.0.0        240.0.0.0         On-link     192.168.56.1    281
        224.0.0.0        240.0.0.0         On-link        10.0.0.75    291
  255.255.255.255  255.255.255.255         On-link        127.0.0.1    331
```

Figure 4 Routing Table on Command Prompt. Source: https://www.howtogeek.com/howto/windows/adding-a-tcpip-route-to-the-windows-routing-table/

Throughout the years, OSPF protocol has been updated several times, but the OSPF version 1 is defined in RFC 1131 [2]. Now, OSPF has been updated to third version of the protocol, making modifications in IPv4 implementation of the protocol.

OSPF mainly focused on pathfinding to a destination on a network, but before that it also has acknowledging mechanism between the routers on a network. This process is essential because every router will update their respective routing tables, therefore completing the metric data between connections in the network. Later the metric data are used to calculate the shortest path using Dijkstra Algorithm.

The OSPF's best features is allows for the creation of areas and autonomous systems, minimizes routing update traffic, highly flexible, versatile, and scalable, and offers unlimited hop count, which is the amount of 'hops' is the amount of routers a datum must pass in order to reach the destination. On its implementation, OSPF protocol is divided into three major parts:

1. Neighbor and adjacency initialization
2. Link-state Advertisement (LSA) flooding
3. Shortest Path First tree calculation

When OSPF is initialized on a router, the router allocates memory for it, as well as for the maintenance of both neighbor and topology tables. The first step is neighbor and adjacency initialization. It is the most essential step of the OSPF protocol. It is a way to establish the adjacency to each router in a network. But in the network, 'adjacent' isn't enough if the routers just connected to each other. Both routers also must be on the active, or Exstart State to be connected and adjacent [7].

To start the connection, one router as the initiator will send Hello packets, which is a starting packet to connect with adjacent router. It consists of the router's ID (RID) to tell the adjacent router its identity.

The RID is not only used to advertise routes, it's also used to elect the designated router (DR) and the backup designated router (BDR). These designated routers create adjacencies when a new router comes up and exchanges LSAs to build topological databases.

The adjacent router will receive the packets, and if it is on the active state, will send back a response packet to the first router. This state is called the Exchange State [7]. After that, the router will send an acknowledgement packet, telling the adjacent router that in the said router's routing table, the adjacent router has been registered as its neighbor. Now the same will happen on the adjacent router to the first router. Figure 5 illustrates the first step of OSPF protocol.

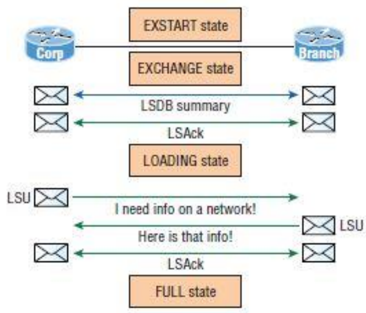
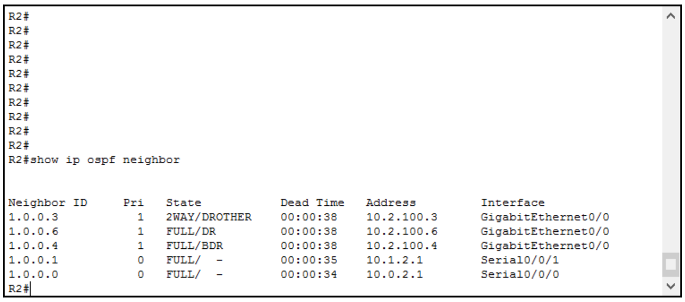


Figure 5 Neighbor and Adjacency Initialization. Source: *CCNA Routing and Switching Study Guide*

After both routers has established connection, now OSPF protocol will update the routing tables of each routers. Now there are information on each neighboring router in their routing tables. The routers also update their routing tables to the information it doesn't have from the neighboring routers' routing tables. This state is called the Loading State [7].

This exchange of information is necessary to update each router with the current network topology. After the information is complete, both routers are in the Full State [7]; it has been fully updated with the network and well connected to their neighbors. Figure 6 shows the neighbor table configuration in the Cisco router's interface.



```
R2#
R2#
R2#
R2#
R2#
R2#
R2#
R2#
R2#
R2#
R2#show ip ospf neighbor


Neighbor ID     Pri   State           Dead Time   Address         Interface
1.0.0.3           1   2WAY/DROTHER    00:00:38    10.2.100.3      GigabitEthernet0/0
1.0.0.6           1   FULL/DR         00:00:38    10.2.100.6      GigabitEthernet0/0
1.0.0.4           1   FULL/BDR        00:00:38    10.2.100.4      GigabitEthernet0/0
1.0.0.1           0   FULL/  -        00:00:35    10.1.2.1        Serial0/0/1
1.0.0.0           0   FULL/  -        00:00:34    10.0.2.1        Serial0/0/0
R2#
```

Figure 6 Neighbor Table for OSPF. Source: https://www.ictshore.com/free-ccna-course/ospf-configuration/

This shows that both routers have been established as adjacent nodes in the network graph. Now both routers will periodically send Hello packets to maintain the connectivity status of neighboring routers. If at some point one of the neighboring routers is deactivated or in down state, the other opposing router will update the network about the change in the network topology with the second step of the protocol.

The next step is the link-state advertisement (LSA) flooding on the network. This is a necessary broadcast to tell all routers in the network that a neighboring connection has been established. This information is used to create network topology from whish the SPF tree can be formed. It used broadcasting as the communication band, so all the routers in the network receive the message.

Each router recalculates its database every time there's a topology change. If you have numerous routers in an area, they'll clearly have lots of links. Every time a link goes up or down, an LSA Type 1 packet is advertised, forcing all the routers in the same area to recalculate their shortest path first (SPF) tree [8]. Predictably, this kind of heavy lifting requires a ton of CPU overhead. On top of that, each router must hold the entire link-state database that represents the topology of the entire network, which results in considerable memory overhead. As if all that weren't enough, each router also holds a complete copy of the routing table, adding more to the already heavy overhead burden on memory [8]. Considering these OSPF factors, it's easy to imagine that in a large network, single area OSPF presents some serious scalability challenges.

The new version of OSPF continues the trend of routing protocols having a lot in common with their IPv4 versions. The foundation of OSPF remains the same. It's still a link-state routing protocol that divides an entire internetwork or autonomous system into areas, establishing a hierarchy.

In OSPF version 2, the router ID (RID) is determined by the highest IP addresses assigned to the router. And as you now know, the RID can be assigned. In version 3, nothing has really changed because you can still assign the RID, area ID, and link-state ID, which remain 32-bit values.

Adjacencies and next-hop attributes now use link-local addresses, but OSPFv3 still uses multi-cast traffic to send its updates and acknowledgements. It uses the addresses FF02::5 for OSPF routers and FF02::6 for OSPF-designated routers. These new addresses are the replacements for 224.0.0.5 and 224.0.0.6, respectively.

Other, less flexible IPv4 protocols don't give us the ability that OSPFv2 does to assign specific networks and interfaces into the OSPF process, but this is still configured under the router configuration process. And with OSPFv3, just as with the EIGRPv6 routing protocols, the interfaces and therefore the networks attached to them are configured directly on the interface in interface configuration mode.

B. Implementation of Dijkstra Algorithm

In networks, every connection between routers have their own bandwidths, which can be modelled as a weighted graph. The vertices of the model graphs are analogous to the routers, and the edges are analogous to the connections, which the edges' weights corresponds to the cost based on the connections' bandwidths.

In the calculation of the cost, the connections' bandwidths will be the reference point of the cost. But the cost's calculation isn't directly affected by the amount of bandwidth a connection makes. Because greater amount of bandwidth a connection has, the better for the path calculation. Instead the cost's calculation is done by using a reference bandwidth as an inverse relationship with the bandwidths. As the bandwidth's amount is increasing, the cost calculated is decreasing. Table 2 shows the conversion from bandwidth amount to cost calculation on the network, with the #0 as the reference bandwidth.

OSPF uses a metric referred to as cost. A cost is associated with every outgoing interface included in an SPF tree. The cost of the entire path is the sum of the costs of the outgoing interfaces along the path. Cost is an arbitrary value as defined in RFC 2338 [8], Cisco had to implement its own method of calculating the cost for each OSPF-enabled interface. Using this rule, a 100 Mbps Fast Ethernet interface would have a default OSPF cost of 1 and a 1000 Mbps Ethernet interface would have a cost of 1 [7].

#	Bandwidth	Cost
0	100000 Kbps	1
1	50000 Kbps	2
2	10000 Kbps	10
3	2000 Kbps	48
4	1544 Kbps	64
5	128 bps	781
6	64 bps	1562

Table 2 Bandwidth to Cost Calculation

The calculation of cost is done inside individual routers and modelled based on the network topology in the respective routing tables. The network can be modelled into an edge-weighted graph with its vertices as the routers, edges as the connection between routers, and edge-weight as the calculated cost of the bandwidths.

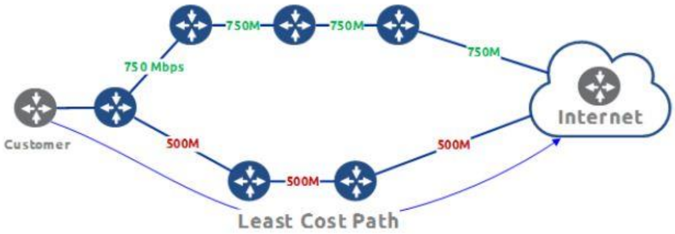


Figure 7 OSPF Calculation of SPF Path to Internet. Source: https://www.cisco.com/c/en/us/support/docs/ip/open-shortest-path-first-ospf/13682-10.html

As the model suggests, the bandwidths can be modelled as the weight on the edges with the calculations in table 2. The routers also served as vertices and the path is made using the Dijkstra Algorithm to reach the destination. Figure 7 displays the SPF path of the network, from the customer router to the internet.

IV. Effect On Modern Networks

OSPF's application has great effects on networks. OSPF's capability to converge a network into such graph model with costs is one of the values that makes OSPF useful in navigating the path. The performance of the tunable and standards OSPF protocols is compared in terms of the number of adjacencies lost in each case. Since no real node or link failure is simulated in the network, all adjacency losses are spurious and thus, a lower number depicts superior performance.

A test was conducted in 2015 by Dillibabau, Akhsay, and Shiny about the performance comparison of routing protocols, which is EIGRP, OSPF, RIP, and IGRP [9]. The test includes sequence simulation, ethernet end-to-end packet delay, and load and throughput.

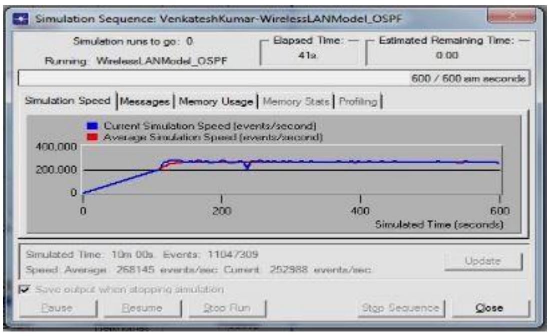


Figure 8 OSPF Performance in Sequence Simulation. Source: *Comparison of RIP, EIGRP, OSPF, IGRP Routing Protocols in Wireless Local Area Network (WLAN) By Using OPNET Simulator Tool - A Practical Approach*

One of the important tests conducted by Dillibabau, Akhsay, and Shiny was the ethernet delay. It is conducted to prove the speed of end-to-end packet transfer in an ethernet connected network. Network delay is an important design and performance characteristic of a computer network or telecommunications network. The delay of a network specifies how long it takes for a bit of data to travel across the network from one communication endpoint to another. It is typically measured in multiples or fractions of seconds. Delay may differ slightly, depending on the location of the specific pair of communicating endpoints. The end-to-end delay can be computed using the following formula:

$$\delta = \frac{\sum_{n}^{i}(CBR_{sent\ time} - CBR_{receive\ time})}{\sum_{n}^{i} CBR_{received}}$$

Where CBR is the constant bitrate of the transmission, and δ is the delay calculated at the given network connection. Because the delay depends only at physical properties, then delays must be lowered and stabilized using the data path choice or the throughput packet delivery rate. Figure 9 displays the performance of OSPF in ethernet delay.

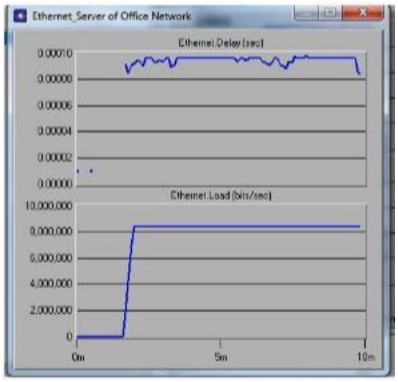


Figure 9 OSPF Performance in Ethernet Delays. Source: *Comparison of RIP, EIGRP, OSPF, IGRP Routing Protocols in Wireless Local Area Network (WLAN) By Using OPNET Simulator Tool - A Practical Approach*

Based on the data, the delay OSPF produces was significantly stable than the rest. Although the starting delay was high, but as the time goes the delay stays the same, thus the reception of the data was not interrupted with change of throughput or disruption in the transmission rates.

In the research by Dillibabau, Akhsay, and Shiny, the conclusion was EIGRP and OSPF protocols are more efficient than other routing protocols in terms of throughput and load. A comparison between different protocols were analyzed and we can suggest that markets like large enterprises, educational institutes, industrial sites can implement EIGRP and OSPF routing protocol for better performance and key catalyst like 802.11a, 802.11g can accelerate the WLAN (Wireless Local Area Network) with the speed to 54 Mbps [9].

Although EIGRP was leading OSPF in terms of converging networks, OSPF has proven to significantly decrease load throughputs due to the optimum SPF path calculated in the protocol.

Another study by Wijaya also comparing the performances of EIGRP and OSPF protocol in dynamic routing of IPv4 and IPv6 networks [10]. The result was given in figure 10. As the data shows, although that OSPF was higher in terms of packets sent multiaccess and non-broadcast multiple access (NBMA) in the IPv6 networks and point-to-point access in IPv4, the difference with EIGRP is not so large (in terms of the amount of packets). Thus, after EIGRP, OSPF is leading in the protocol of routings in modern networks.

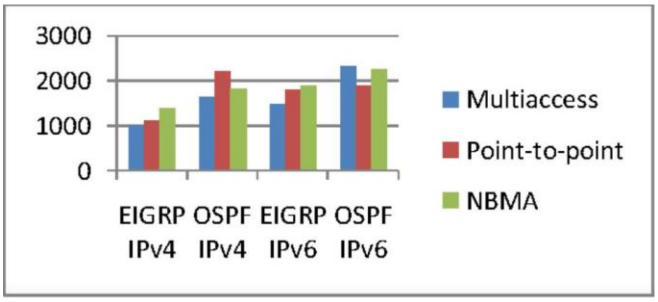


Figure 10 Total packet sent when routing info exchange process
Source: *Performance Analysis of Dynamic Routing Protocol EIGRP and OSPF in IPv4 and IPv6 Network*

OSPF and EIGRP will distribute routing information between routers in the same autonomous system. The research will find how routing protocol works and compare those dynamic routing protocols in IPv4 and IPv6 network. But the conclusion of the research is that in the simulation of different network topology, the data shows that EIGRP are much better than OSPF in many different network topologies.

V. Conclusion

OSPF is a network routing protocol that uses the Dijkstra Algorithm to find the best route (SPF path) to a given destination in the network. Because of the optimal path traversal of data stream, OSPF offers high performance in the modern networks, although it was defeated by the newly enhanced IGRP protocol (EIGRP), OSPF is one of the leading protocols of routing in modern networks.

VI. Acknowledgment

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References

[1] https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-741490.html. (Accessed 4 December 2019)
[2] https://tools.ietf.org/html/rfc1131. (Accessed 4 December 2019)
[3] Dijkstra, E. W. (1959). "A note on two problems in connexion with graphs". *Numerische Mathematik*. **1**: 269–271
[4] http://www-set.win.tue.nl/UnsungHeroes/machines/armac.html. (Accessed 4 December 2019)
[5] Frana, Phil (2010). "An Interview with Edsger W. Dijkstra". Communications of the ACM. 53.
[6] Fletcher, Peter; Hoyle, Hughes; Patty, C. Wayne (1991). Foundations of Discrete Mathematics (International student ed.). Boston: PWS-KENT Pub. Co.
[7] Lamle, Todd. (2015). "CCNA Routing and Switching Study Guide". Colorado: Sybex. 857.
[8] https://tools.ietf.org/html/rfc2338 (Accessed 5 December 2019)
[9] U. Dillibabau, Akshay, M. Lorate Shiny. (2015). "Comparison of RIP, EIGRP, OSPF, IGRP Routing Protocols in Wireless Local Area Network (WLAN) By Using OPNET Simulator Tool - A Practical Approach"
[10] Wijaya, Chandra. (2011). "Performance Analysis of Dynamic Routing Protocol EIGRP and OSPF in IPv4 and IPv6 Network".

Pernyataan

Dengan ini saya menyatakan bahwa makalah yang saya tulis ini adalah tulisan saya sendiri, bukan saduran, atau terjemahan dari makalah orang lain, dan bukan plagiasi.

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