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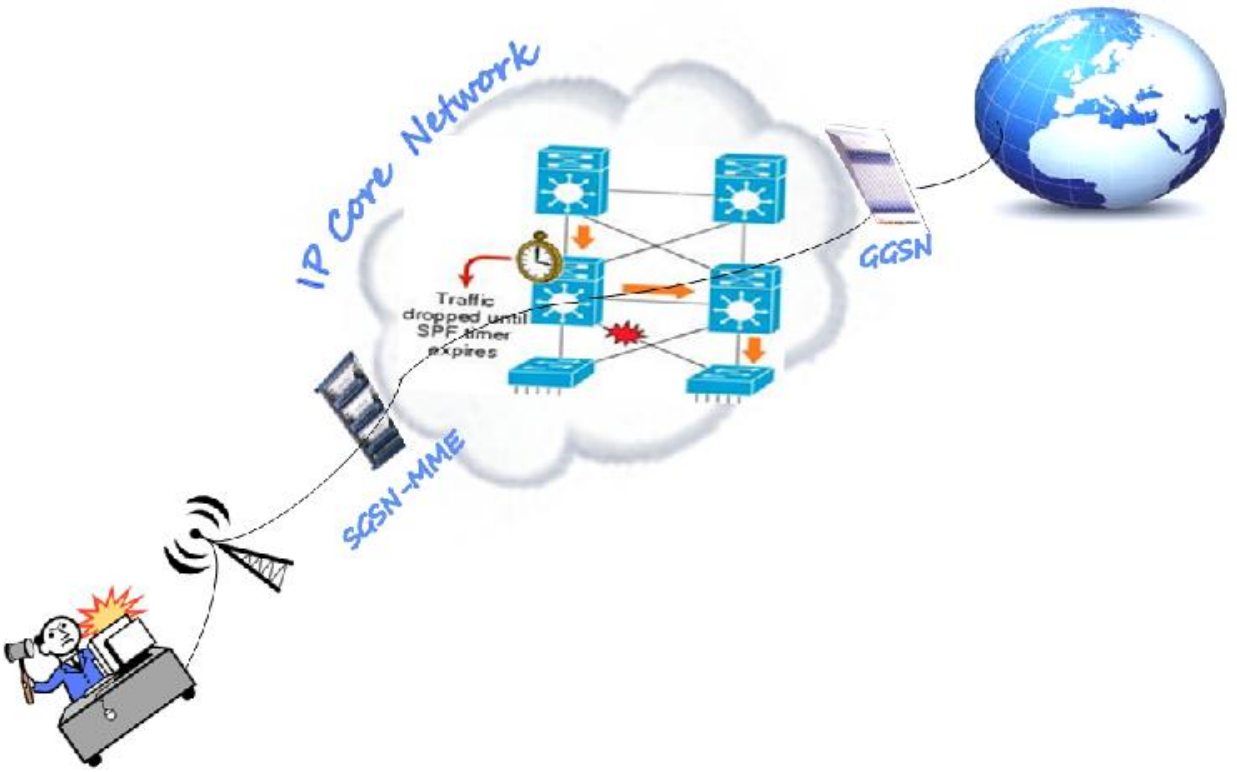
OSPF Convergence Times



Master of Science Thesis in the Programme Networks and Distributed Systems

Yonas Tsegaye ,Tewodros Geberehana

Department of Computer Science and Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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Master's thesis _____

Abstract

Following the merger of telecom and IP networks, there has been a sharp rise in the number and types of multimedia applications such as interactive real-time Voice/Video over IP. This has put a new service requirement on IP networks and thus has required the IP network solution providers and telecom operators to device new techniques and optimizations to meet the needs of these business critical applications. One way to address these demands is to implement fast and efficient routing mechanism as the data packets are exchanged end to end. Open Shortest Path First (OSPF) is one of the widely deployed routing protocols responsible for this.

Most of the important operations of OSPF that contribute to fast convergence such as fast failure detection, shortest path computation and flooding are controlled by timers. These timers, as specified in RFC2328 are fixed and too conservative for modern networks. Today, there has been an increasing effort to make these timers dynamic so that the values are determined based on the experienced network load and stability instead of a preset static value.

This thesis is in part a thorough assessment of the state of the art on OSPF timers and fast convergence techniques. The other major contribution of this work is the implementation of the Link State Advertisement (LSA) throttling algorithm as an adaptive technique to control unwanted LSA generations at times of network instabilities. We used two simulators; OPNET Modeler (Academic Version) because of its advanced graphical user interface (GUI) and result analysis tools, and the open source OMNET++ for its open OSPFv2 source code. The outcome of this thesis therefore the work done on literature review which embraces a set of recommended techniques to achieve sub-second convergence, a simulation supported analysis of the associated stability issues in terms of convergence time and CPU load and also the introduction of our own pseudo code and implementation of the LSA throttling algorithm, originally introduced in CISCO 12.0(25) S. The simulation work has proved the LSA throttling algorithm indeed improves a network's convergence speed and can be deployed on any size OSPF network including large ISP networks consisting of thousands of routers.

Keywords,

OSPF, OMNETPP, OPNET, LSA Throttling, SPF Throttling, Dynamic timers, Sub-Second Convergence, AS, Area.

Preface

This thesis was written for Chalmers University of Technology, Gotebörg, Sweden as part of the requirement for the Master of Science degree in Networks and Distributed Systems Program. The work was done at Ericsson AB, Gotebörg, Sweden by Yonas Tsegaye and Tewodros Geberehana.

The report is the result of literature studies including a brief review of Ericsson's internal documentation related to IP connectivity and routing in SGSN-MME and also of the simulation experiments conducted on OPNET Modeler and OMNET++ simulators. It's compiled with a close guidance and advisory of Christofer Kanljung, the thesis supervisor at Ericsson. We are immensely thankful to his supervision and invaluable input to this thesis work. We also would like to thank Ingemar Reinholdt, the former manager at Link and IP Routing for his warm welcome and encouragement at the startup of this project. We would like to dedicate a line here to thank all the employees of the department for their company and encouragement.

We are also highly indebted to our examiner and advisor at Chalmers, Dr. Elad Michael Schiller. We appreciate his guidance and unreserved dedication to help the work in every way he could.

Above all, we would like to give praise to our God for giving us the courage to finish this work.

List of Abbreviations

3GPP	3rd Generation Partnership Project
ABR	Area Boarder Router
AS	Autonomous Systems
ASBR	Autonomous System Boundary Router
BDR	Backup Designated Router
BFD	Bidirectional Forwarding Detection
BGP	Boarder Gateway Protocol
DR	Designated Router
EPG	Evolved Packet Gateway
ETWS	Earthquake and Tsunami Warning System
FDDI	Fiber Distributed Data Interface
FIB	Forwarding Information Base
GGSN	Gateway GPRS Network
GSM	Global System for Mobile Communications
ICT	Information Communication Technology
IETF	Internet Engineering Task Force
iFIB	Incremental Forwarding Information Base
IGP	Interior Gateway Protocol
IOS	Internetwork Operating System
IP	Internet Protocol
ISDN	Integrated Digital Subscriber Line
ISIS	Intermediate System-to-Intermediate System
ISP	Internet Service Provider
iSPF	Incremental Shortest Path First
LAN	Local Area Network
LSA	Link State Advertisement
LSDB	Link State Database
LTE	Long Term Evolution
MME	Mobility Management Entity
MPG	Mobile Packet Gateway
NBMA	Non-Broadcast Multi-Access Network
NSSA	Not So Stubby Areas
OMNETPP	Objective Modular Network Test bed in C++
OPNET	Optimized Network Engineering Tools
OSPF	Open Shortest Path First
PDN	Public Data Network
PIU	Protocol Interface Unit
POS	Packet over SONET
PRC	Partial Route Calculation
PRC	Partial Route Computation
PVC	Permanent Virtual Circuit
PWS	Public Warning Systems
RDI	Router Dead Interval

RFC	Request for Comment
RIB	Routing Information Base
RIP	Routing information protocol
RN	Radio Network
SDH	Synchronous Digital Hierarchy
SGSN	Serving GPRS support node
SONET	Synchronous Optical Network
SPF	Shortest Path First
SPT	Shortest Path Tree
TCP	Transmission Control Protocol
TLV	Type-Length-Value
TTL	Time to Live
UDP	User Datagram Protocol
VOIP	Voice over IP
VPN	Virtual Private Networks
WAN	Wide Area Network
WCDMA	Wideband Code Division Multiple Access
WLAN	Wireless Local Area Network

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1. Introduction

Routing is a process of selecting an optimal path (route) in a network using which data packets are transferred from a given source to a destination. The Open Shortest Path First (OSPF) is one of the prominent Interior Gateway Protocol (IGP) in IP networks today. It is a link state routing protocol that uses the Shortest Path First (SPF) algorithm to determine the current shortest path from a node to all other nodes in a network. OSPF makes use of different set of timers that come in to play while performing most of the important operations such as SPF computation, Link state Advertisement (LSA) generation and flooding. These operations highly impact a networks' convergence speed.

This literature studies the impact of decreasing the value of traditional OSPF timers on network convergence and stability, see [7] [13] to name a few. While these studies generally show that sub-second failover can be achieved through the use of sub-second OSPF timers, the implementation highly depends on the existing network resources, frequency of failures and experience. This report, apart from presenting the key techniques on OSPF fast convergence, also discusses the impact of decreasing OSPF timers on network stability. The LSA throttling feature [12] as an adaptive timer technique to delay LSA generation at times of frequent link flaps is also implemented and discussed.

Ericsson has long been renowned for its world best telecom solutions and customer reputations. It has been the leader in the market and the pioneer in its cutting-age researches ever since its inception. Between 35 to 40 percent of the world's mobile traffic passes through the Ericsson's networks spread all over the world. The success comes from the combined effort of extensive researches made in each operational elements and levels.

The Ericsson's Evolved Packet Core (EPC) is a key element in the realization of the mobile broadband technology. It's a flat IP-based core network architecture based on the Third Generation Project Partnership (3GPP) standardization. EPC is the main channel between the high speed Radio Network (RN) and the external world. The following picture shows the 3GPP EPC architecture.

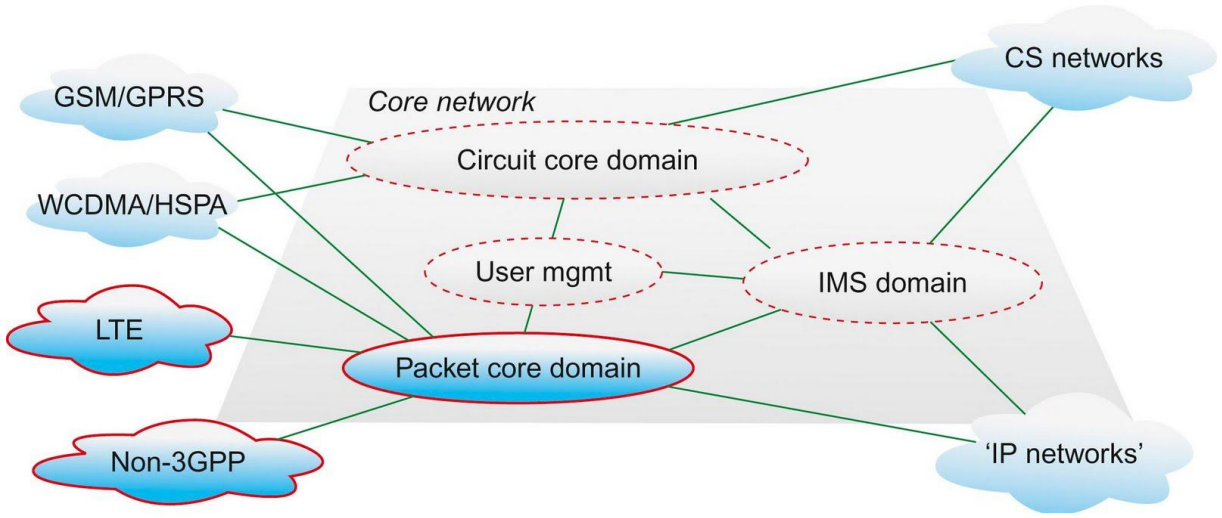

Figure 1.1: The 3GPP EPC architecture

The top three clouds to the left represent the different Radio Access Networks (RAN) and the fourth one shows any radio access network such as WLAN or WiMax which is not part of the 3GPP specification. The circuit core domain is responsible for all circuit switched services over GSM and WCDMA whereas the user management maintains subscribers' information and also supports mobility within the different domains. The last but the main component is the packet core domain that takes care of all packet switched services for all the radio access technologies.

The packet core technology in Ericsson provides converged IP routing facilities for all mobile access services shown in Figure 1.1 The two basic entities of the Ericsson's packet core network are Serving GPRS Network (SGSN) and Gateway GPRS Network (GGSN) .With the advent of the 3G and 4G solutions such as WCDMA and LTE, these entities have seamlessly transitioned to SGSN-MME and GGSN-MPG/EPG respectively with no major hardware changes but simple software upgrades. SGSN-MME is responsible for providing packet data switching and mobility management services for all the radio access networks, whereas GGSN-MPG/EPG is the gateway between the packet core and the external network. Its key functions include traffic prioritization, charging, deep packet inspection and authentication among others.

The figure shows part of the SGSN in the GPRS network and the MME unit in the EPC, altogether referred to as SGSN-MME. The dashed lines represent the internal IP traffic (control traffic) and the solid ones represent the external data traffic (payload traffic).

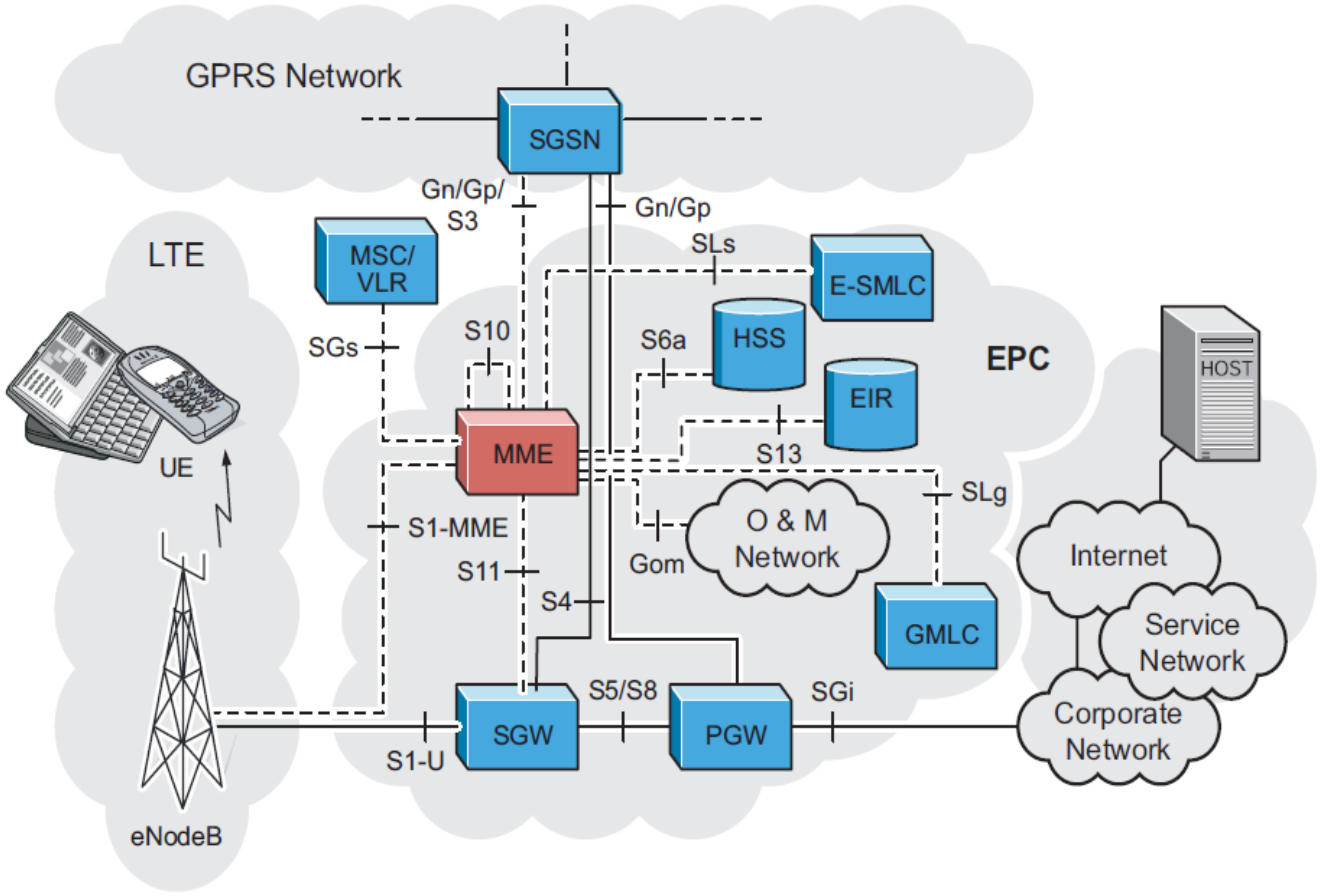

Figure 1.2: External Interfaces for SGSN-MME [34]

1.1 IP Routing in SGSN-MME

The SGSN-MME supports IP routing of IP packets received and sent on all internal and external interfaces of the SGSN-MME shown in the above figure. The traffic is separated into a number of trusted Virtual Private Networks (VPNs) for enhanced security. The figure below shows the routing in SGSN-MME from a logical perspective with two VPNs each with alternative (redundant) routing paths. The SGSN-MME architecture allows the same VPN to be configured over multiple Protocol Interface Units (PIUs) using the same IP address for load sharing purpose and also a single PIU can run multiple VPNs separated by VLANs.

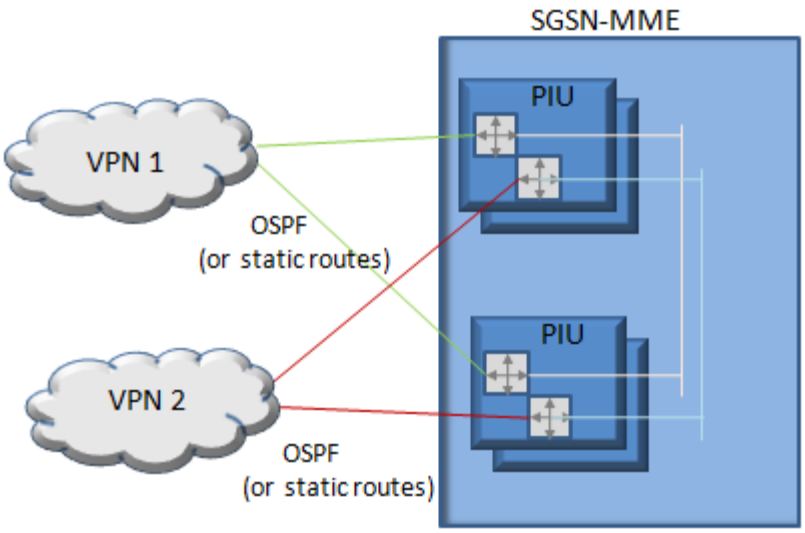

Figure 1.3: Logical overview of the routing in SGSN-MME

The IP routing in SGSN-MME makes use of dynamic routing protocols such as OSPF as well as static routes where necessary. Static routes with multiple next hop addresses are supported based on a reliable load sharing scheme. In such cases, Bidirectional Forwarding Detection (BFD) is typically used to monitor the IP gateway addresses for fast switching to a different gateway when the current gateway is unreachable. An extended review of BFD can be found in chapter 4.

1.2 Objectives

The objectives of this project are as follows:

- Find out the state of the art in OSPF convergence.
- Check if there are any applicable researches within this area.
- Investigate what set of traditional and vendor specific timers are in use today.
- Find out which timers that might be tweaked and find out if there is any algorithms that can be used to be adaptive to different levels of stability in the network.
- Analyze the dependency among CPU run time, network stability and convergence time for different set of timers.
- Measure the CPU run time, SPF computation and flooding times using appropriate tools and methods.

The outcome of this work is partly a recommendation of the state of the art techniques on OSPF timers and fast convergence (chapter 4). The work includes a simulation supported analysis of a network's stability levels using various set of timers (section 5.1.4). The implementation and analysis of the LSA throttling algorithm is also the other major contribution of this work (section 5.1.5). The LSA throttling, also known as LSA generation delay is a dynamic technique first proposed by CISCO

Systems, Inc [12] to limit excessive and unwanted LSA generations at times of network instability. The technique allows fast convergence taking the network's stability into consideration. As part of the implementation, this document also introduces a pseudo code of the LSA throttling feature. The experiments and results from this work can be easily scaled up to any size OSPF network including large scale ISP networks consisting of hundreds and thousands of routers.

1.3 Problem description

One of the strongest points of OSPF has traditionally been that it provides a network convergence time in a couple of seconds. The convergence time is the time from a topology change until all other nodes in the network recalculate their shortest path to all other nodes. The convergence time determines how fast the routers adapt their routing tables to topological changes.

The demands on IP networks have risen over time since OSPFv2 was first introduced due to more mission critical use of networks and due to the convergence of the telecom and IP networks. There is now demand for sub-second convergence of OSPF networks. Recent advances in OSPF implementation shows that this can be addressed through various tweaks of OSPF timers. But it's not enough to just decrease the different timers; the impact on network stability and on CPU cost has to be analyzed as well.

1.4 Scope and Limitations

The simulation work and results in this thesis are done based on the application of OSPFv2 on point to point links according to the RFC 2328. The discussions on fast convergence techniques mainly focus on the standard as well as the newly introduced (vendor specific) timers. Optimization techniques from traffic engineering (TE) extensions point of view are not part of this work. This document doesn't discuss details of OSPFv3 and/or its application on ipv6. OSPFv3 is discussed in comparison with OSPFv2 on some points where we thought was worth mentioning.

The simulation tools used in this project were not readily provided by Ericsson. As part of the thesis, we had to make a survey to choose a suitable tool from the open source domain, and that has required us a considerable amount of time during the early phase of this project. After a thorough investigation of the available choices, OPNET modeler 14.5(education version) and OMNET++ 2.2.1 were found suitable for the work .A brief walkthrough of the selected tools is presented in chapter 5.

1.5 Related Work and Contribution

OSPF is a relatively matured and widely studied routing protocol. A lot of researches and publications have been done on how to improve its convergence and stability aspects. Fast convergence deals with boosting a network's speed of information exchange to come to a consistent state whereas the stability aspect assures the network won't break while doing so.

Anindya B. John G. in [9] made an experimental study to find out the optimal hello timer for fast convergence. Their simulation results on large ISP network consisting of 292 nodes and 765 links shows that the hello interval can be safely reduced to 275 milliseconds for fast convergence without impacting the network's stability. The authors in [7] made a similar investigation on finding an optimal value for static hello timers. They argue that it is unsafe to reduce the hello timer below 500

milliseconds but instead it's possible to speed up the convergence by prioritizing the processing of hello packets over the other types of OSPF messages. They also suggest the use of a set of conservative approaches such as Packet Over SONET (POS) for fast failure detection, dynamic timer usages for LSA generation and SPF computation as recommended fast convergence practices. On the other hand, the authors in [8] and [36] proposed a dynamic mechanism to tune hello timer based on the experienced congestion level. The technique in [8], also explained in chapter 3, works in such a way that an OSPF peer increases its hello interval exponentially whenever it experiences a loss of hello messages for more than a given threshold. The other similar technique proposed in [36] instead uses a scheme called Dynamic Router Dead Interval (RDI) where the RDI is dynamically adjusted based on the hello drop rate computed over a certain period of time. Cisco Systems, Inc. has devised a technique to dynamically adjust the interval between each LSA generations called the *minLSAInterval* which is one of the OSPF timers that attributes the most for fast convergence. The technique is discussed at high level in [12].

One of the main contributions of this project is to implement and evaluate this algorithm in an OSPF network using 1 millisecond hello interval and 4 millisecond *routerDeadInterval*. The original plan was to use sub second hello timers but that was impossible due to simulator limitations. As part of the implementation, the paper also presents the pseudo code of the algorithm (section 5.1.5.6). The paper also contains theoretical discussion of the state of the art techniques on OSPF fast convergence as well as an experimental evaluation of the relationship between different sets of OSPF timers and network stability issues.

1.6 Structure of the dissertation

This dissertation is organized as follows:

Chapter 2 discusses some of the topology change events in an OSPF network and the convergence process following the change.

Chapter 3 presents OSPF fast convergence techniques.

Chapter 4 gives a mix of the different techniques to achieve sub-second convergence along with similar experiences shared from literature review.

Chapter 5 discusses the work on the selected simulators and the analysis. It starts with a brief survey of network simulators and advances further into the work done on the selected simulators.

Chapter 6 concludes the discussion by summarizing the main points related to OSPF sub-second convergence.

Appendix 1 discusses the basics of OSPF.

2. OSPF Convergence Process

This chapter discusses the convergence process and the major factors affecting the convergence process. Various types of topological changes as a cause for the convergence process are presented.

2.1 Routers Distributed Architecture

A router is a device that is responsible for forwarding packets between interconnected devices. A routing protocol is a rule that governs how communications should be done between communicating devices. Routers relate the IP header of a packet with the entries in their routing table to determine the next best hop to forward the packet to. Modern routers have a distributed architecture that works independently, the routing engine (control plane) and the packet forwarding engine (data plane). The forwarding engine which is a switch fabric is used to forward between the inbound and out bound interface of a line card. Therefore, the control plane takes care of the routing protocol and the data plane takes care of the forwarding functions.

The control plane is responsible in constructing and maintaining the RIB from which the FIB is constructed; the RIB consists of best paths to reach different nodes in a whole network [6]. The data plane performs packet switching, route lookups, and packet forwarding. It basically sends out packets from port to port based on a longest-prefix match and an access control list that filter out the packets. The FIB contains the least required information to forward the IP packet, the next hop and the associated outgoing interface.

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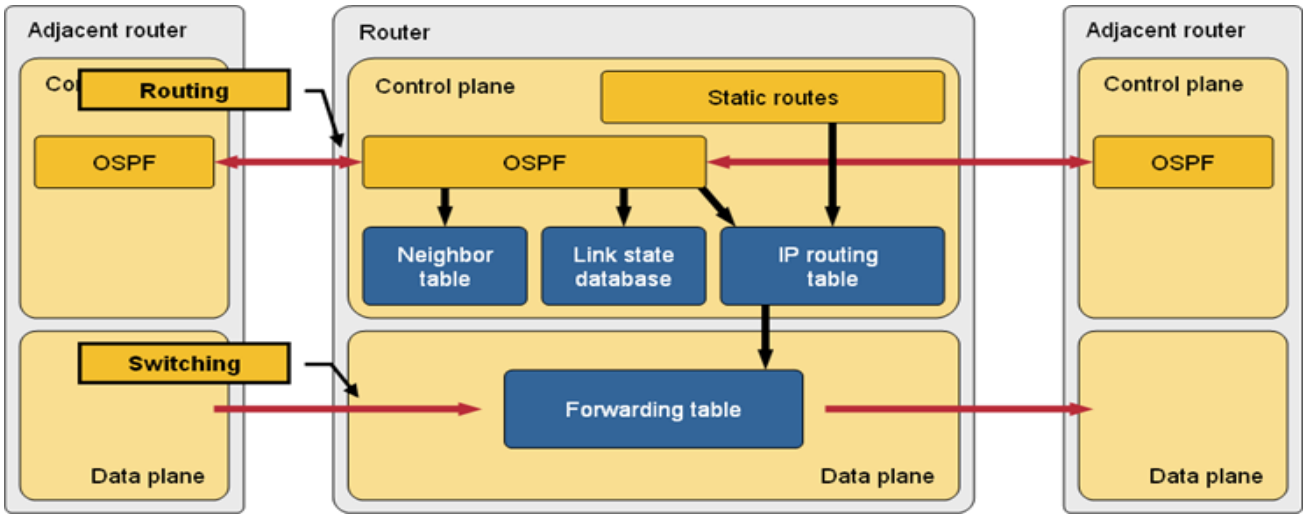


Figure 2.1: The control and data planes

The forwarding process includes checking the IP headers and the TTL (Time to Live) of the incoming packet, decrementing the TTL and updating the IP header checksum and look up the destination IP address, in the FIB, to decide the next hop address. Routers perform SPF re-computation up on the arrivals of LSA updates and the change is reflected on the forwarding table via the RIB. The

distributed nature of the router architecture reduces the load on the CPU. It can also allows the data plane to keep forwarding packets to neighbors even when the control plane reboots for some activities like updating its software.

2.2 Inbound packet processing in a router

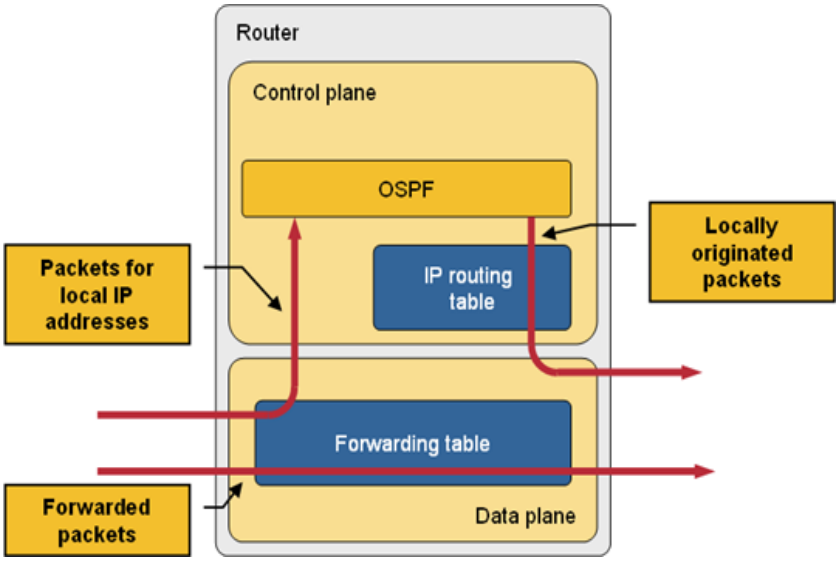


Figure 2.2: Processing of inbound packets

An incoming IP packet, in most implementations, is first processed by the data plane which may be sent to the control plane or the outgoing interfaces based on the nature of the packet. As can be seen in Figure 2.2, packets destined for other routers are forwarded directly without the need to send it to the control plane. Some special packets like *hello* packets and routing updates need to be forwarded to the control plane.

2.3 Topology changes in an OSPF network

A topology change in an IP network can result from failures in the network components or addition of new network equipment. Failures can occur due to planned maintenance, software and/or hardware problems or errors introduced by humans. The impact of a failure can vary based on its nature. Topology changes are reflected through LSA updates to all other nodes in a network. When a link failure occurs, it is detected through the underlying error detection mechanisms and the change is reflected through LSA update that is flooded across the network. The SPF calculation is scheduled up on the arrival of updates in a node, which leads to the ultimate goal of installing a new alternative route in the network. A router's OSPF convergence process starts from the time an error is detected until a new alternative route is installed in the router. The duration that takes a router to adapt the change is termed as the convergence time of the router.

2.4 Associated problems with OSPF convergence

Topology changes in a network are usually followed by one or more of the following issues until the network adapts the change. Data packet losses or unordered deliveries, CPU/memory consumptions due to extra packer processing and routing table calculations can be mentioned as examples. Such excessive usage of resources, in the worst case might have the potential to meltdown the whole network.

2.5 OSPF convergence process

OSPF is an interesting protocol since it involves a small time to install new route and re-route traffic once a failure occurs. The OSPF convergence process is composed of the following processes.

- Detecting changes in network status
- Generating a new LSA to reflect the change
- Flooding the LSA in the OSPF network
- Performing SPF calculations on each router that receives the update information
- Updating the RIB/FIB on each router

It is a requirement for all routers affected by topological changes to go through the process of convergence and the time involved depends on how large and complex a network can be. In the convergence process, the desirable effect is to achieve a faster convergence time. As routers converge quickly it is relatively easy to avoid the problems mentioned in section 2.4.

2.6 Adding node to a converged network

Assuming a converged network in the first place Figure 3.3, adding a new router called *New_node* results in the topology change of the network .As a result, the network is required to go through the steps mentioned below so as to maintain a synchronized information about the network topology.

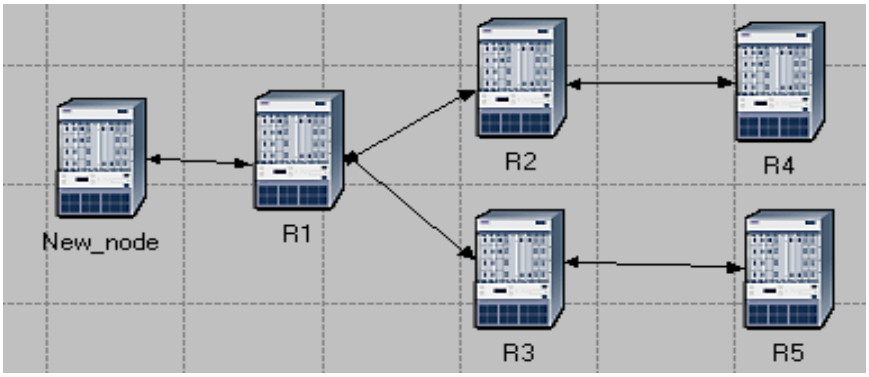


Figure 2.3: Adding router to a converged network

The following steps are involved in the convergence process.

1. The new node (New_node) sends a *hello* packet to R1. R1 reply using a *hello* packet to confirm the discovery. The two nodes then decide to form adjacency.
2. The new node and R1 exchange Database Description Packets. R1 had the latest LSA of all the

   Routers in the network except the LSA of the node New_node. The New_node has only information about itself.
3. The new node sends a Link State Request packet to R1, requesting the LSAs of all the routers and receives it in the form of Link State Update from R1.
4. R1 sends a Link State Request packet to New_node and New_node sends its LSA to R1 as a Link State Update packet. The two nodes have now synchronized their LSDBs, followed by SPF tree calculation and both install their new routing tables.
5. R1 sends a link state update packet to its adjacent routers R2 and R3, after synchronized with New_node. The update packet contains the LSA learned from New_node. R2 and R3 perform SPF tree calculation after receiving the update from R1.
6. R2 and R3 flood the update to R4 and R5 respectively, then both receiving routers performs their own SPF tree calculation and install their own respective routing tables.

2.7 Factors that affect the OSPF convergence process

A network's convergence process consists of the following major operations [5] [7].

1. The time it takes to detect the change that occurred in the network.
2. The time it takes to propagate the event in the network this includes both the LSA origination and flooding.
3. The time it takes to perform SPF tree calculations.
4. The time it takes to build the forwarding table in each router. Hence, the total convergence time for an OSPF network is given by the formula.

Convergence Time = Failure_Detection_Time + Event_Propagation_Time + SPF_Run_Time + RIB_FIB_Update_Time

The convergence speed can be affected by a number of factors including the type of error detection method used , network congestion, diameter of the network, processors load due to routing protocols, and the SPF parameter used in the convergence process. Figure 2.4 shows the timers involved in the convergence process.

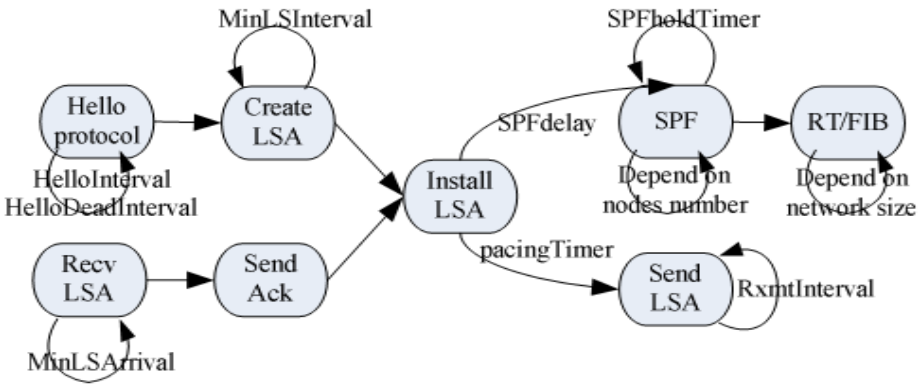


Figure 2.4: Timers in an OSPF network convergence [8]

The above figure shows the different timers that are involved in the OSPF convergence process. Some of the timers are specified in the RFC 2328 and others are vendor specifics. The *hello* protocol works with its associated *HelloDeadInterval* to detect failures. The *MinLSInterval* and the *MinLSArrival* timers are used to determine the rate at which LSAs are generated or received respectively. Since LSA flooding is a reliable process, it involves sending acknowledgments up on the receptions of LSAs. Unacknowledged LSAs are resent upon the expiry of the *Rxmtinterval* Timer. The SPF computation includes *SPFholdTimer* and *SPFdelayTimer* that are used in commercial routers to prevent frequent computation of the SPF at times of stormy LSA generations. The *pacingTimer* is vendor specific and is used not to overwhelm a neighbor during the flooding process. The RIB/FIB update is the ultimate goal of the convergence process after a successful SPF computation. This process takes the maximum share in the convergence process and is mainly depends on the number of updated prefixes and the network size.

2.7.1 Fast Failure Detection Methods

In order to achieve a faster convergence speed in a network the failure detection mechanism in OSPF network plays a great role; the faster a change is detected in a network topology, the better convergence speed the network achieves. Failures in a network can be detected with the help of the *hello* protocol, BFD (see chapter 3) or using hardware based failure detection mechanisms like packet over SONET that can provide error detection mechanism in tens of milliseconds, though its implementation might be uneasy [7].

Periodic *hello* packets are exchanged among neighboring routers. A router maintains an inactivity timer for each neighbor it is adjacent to and this value is reset upon the reception of a *hello* packet from its neighbor. If a failure occurs at a neighbor after the reception of the last *hello* packet, a router can detect the failure using its *HelloDeadInterval* time which in this case is 40 sec (the inactivity timer). Using a *HelloDeadInterval* time of 40 seconds is one of the drawbacks of the *hello* protocol implementation in areas where VOIP (Voice over IP) and PWS (Public Warning System) are deployed. The expiration of the inactivity timer causes the braking down of the adjacency between neighbors and results in the generation of a new LSA. Therefore, the *HelloDeadInterval* timer is the time that plays one of the major roles in the OSPF failure detection time which highly attributes to the

convergence speed. By reducing this timer to an optimal small value, the failure detection time can be improved.

2.7.2 Event Propagation

In an OSPF network an LSA can be used to reflect the status of a network, a router LSA describes the link states of a router in a network. Once a failure is detected in a network, propagating the change to all routers in the network is another factor that affects the OSPF convergence speed. To control the frequency of the LSAs generated up on changes in a network, RFC 2328 recommends that every two LSAs should be sent within 5 seconds interval; the so called *MinLSInterval* .

The event propagation can be affected due network congestion that may be caused by LSA storms or other timer effects associated with LSA generation and flooding. For a router affected by change to generate an LSA, it relies on the time of the underlying error detection mechanism and the chosen *MinLSInterval* value. The flooding process includes the delay that occurs at the receiving routers which is the *MinLSArrival* value (the inter-packet arrival time) plus the *pacingTimer* applied by the sending routers and the delay that may be introduced at the time of propagation. Depending on the nature of the network, an LSA storm can result due to any of the following factors.

- A flapping Link/router.
- Fiber cuts resulting in one or more link failures
- Software version change resulting in refresh of all LSAs in the system or
- Due to the periodic, 1800-second, LSA refreshes time in the network.

The flooding scope of a topology change can vary depending on the type of the topology change that occurred. A router, network and summary LSAs are flooded throughout a single area where as a new AS External router LSA might be flooded to all the areas within an AS. Having a small *MinLSInterval* value can help achieve fast convergence but keeping it to zero is not recommended as it highly affects the routing stability and consumes resource. To balance the need for both convergence and the stability of a network, different vendors like Cisco and Junipers have implemented exponential back off algorithm for LSA generation called LSA throttling (see chapter 3 for details).

2.7.3 SPF Calculation

LSAs that reflect topological change are followed by a route table calculation and updating the FIB on the line cards. In an OSPF network each node making itself as a root node, constructs the SPF tree using the Dijkstra shortest path first algorithm. The Shortest path resulting from the SPF calculation is the optimal shortest distance from a source to a destination. At the end of the SPF calculation the optimal routes are populated in to the routing table and this result is reflected to the Forwarding Information Base (FIB), depending on the router's architecture. The SPF computation is the function of the number of nodes in the network and the number of prefixes advertised.

Some implementations follow the traditional approach in which SPF is calculated on every new LSA arrival which requires a high CPU utilization. To avoid a continuous route calculation and minimize the router's processor consumption, commercial routers introduce the *SPFholdTimer* and the *SPF-*

delayTimer (see Figure 2.4 above).The *SPFholdTime*r specifies the time gap between two consecutive SPF calculations. The *SPFdelayTimer* specifies the time that a router should wait to perform the SPF calculation after receiving the first LSA in an attempt to include more LSAs in to the calculation.

In a stable network, it is desirable to have the *SPFholdTimer* to be small to achieve fast convergence, since there is not that much topological change that may occur in the network. In unstable network, where there are frequent changes in the network topology, having a small value of *SPFholdTimer* could result in a frequent SPF calculation. As a result, in such network large intervals in the SPF calculation is preferable to accumulate several changes and execute them at once.

Both the *SPFholdTimer* and the *SPFdelayTimer* help achieve stability in a network but reduce the speed in which a network converge to a new topology. The Cisco routers, after 12.2(14) version, implements a simple exponential back-off timers to balance the need for fast convergence and stability of a network under any circumstance. In order to optimize the routing table calculation another alternative method of scheduling the route table calculation such as LSA correlation and iSPF calculation methods have been suggested.

2.7.4 Routing Information Base (RIB)/ Forwarding Information Base (FIB) Update

RIB also named as routing table, contains reachable information and the associated cost for each route. Routes are installed either in static or dynamic way. To reflect changes in a topology OSPF performs RIB updates following the SPF calculations. Depending on the type of router architecture the RIB can be propagated further to the forwarding table.

The RIB contains the destination network ID, the costs associated with the interface and the next hop address that is going to be used as a gateway to forward incoming packet. Forwarding information Base is a copy of the routing table but it contains the least required information to forward an IP packet. The FIB may not be required to track the whole paths and their corresponding metrics to reach a network. The FIB is optimized for forwarding efficiency or for fast lookup of destination addresses. When packet meant for other nodes arrive at some router the FIB tries to quickly forward the packet to the next hop.

A successful SPF calculation is followed by the RIB/FIB update, which is the ultimate goal. The update time is linearly dependent on the number of modified prefixes that can greatly affect the convergence time of a network [8]. The impact can take a considerable amount of time in large networks. To improve the update time some routers use a proprietary method called iFIB that reflects only the changed part than to construct the FIB from a scratch.

3. OSPF Fast Convergence Techniques

As discussed in the previous chapters, it is generally possible to achieve fast convergence by setting the timers to a lower value. However, it's equally important to analyze the associated impact on network resources (CPU, memory, bandwidth, etc.), especially on networks with frequent instabilities. Knowing the optimal settings of these timers has always been a challenge for one reason that it's highly dependent on a number of generic factors including the network's expected traffic/congestion level, number of nodes/links and other physical link constraints.

This challenge has led to the evolution of what we call dynamic timers**;** timers that can change adaptively with the experienced network behavior. Nowadays, most of the optimizations in OSPF lay on the implementation of dynamic timers which can be preferably introduced at various operational levels; starting from hello packet origination to LSA generation, Shortest Path First (SPF) computation, flooding and FIB updates. This chapter assesses some of the state of the art techniques on the use of dynamic timers and also a few other optimization techniques.

3.1 Dynamic Hello Timers

Hello timers are one of the integral components of many routing solutions. They help discover neighbors and detect failures. The OSPFv2 implementation based on RFC 2328 specifies a fixed *hello* interval of 10 seconds which is quite large according to modern researches and experience [7] [9]. With the rapid increment of modern day routers computing power, it has now become a common sense to lower the hello interval to a millisecond range. While it's generally safe to do this on stable networks, it might have some undesirable effects on unstable networks with frequent link/node flaps and congestions. In these and similar situations where the CPU is kept busy, the hello timers may not be timely processed and assumed to be lost (*hello* omission). The frequent omission of *hellos* makes the neighbor relationship to go up and down and the neighboring routers to generate LSAs that reflect this. This in turn forces all routers in the network to add and delete a particular route every now and then, causing a network wide route flap and disruption. Therefore, In the presence of such flaps, an implementation might prefer to temporarily break the communication between adjacent neighbors over the unstable link in an attempt to discourage the availability of the route and avoid the resulting route flap. Dynamic hellos are designed with that in mind; to suppress the route flaps caused by link flaps in point to point OSPF networks.

The dynamic *hello* techniques, as detailed by the authors in [8] makes use of the *hello_tune* timer assigned for each active interface. The router monitors the presence/absence of instabilities (route flaps, in this case) within the *hello* tune interval. If, within the *hello* tune period, a routers experiences a *neighborDown* event (due to the firing of the inactivity timer) more than a given threshold amount, the router doubles its *hell*o interval. In doing so, the router presumes the presence of a route flap due to a link flap and the doubling of the *hello* interval causes a *hello* mismatch with its neighbor. As two OSPF neighbors should have the same *hello* interval, this variation causes the neighbor relationship to be temporarily suspended until the other neighbor also doubles its hello interval, which is more likely to happen before the first router doubles its *hello* interval for the second time because the former has a smaller *routerDeadInterval* . Once the other neighbor has doubled its *hello* interval, the adjacency

will recover once again with an increased *routerDeadInterval* this time. If the flap continues for the next *hello_tune* interval, the router once again doubles its *hello* interval (exponential growth) and the whole process continues once more. With the absence of such flaps within the *hello_tune* period, the *hello* timer is reset to its default value. The main objective behind this technique is to avoid route flaps by masking link flaps within the increased *routerDeadInterval*. The maximum threshold for the *hellos* is set to 10 seconds and the initial value is set to 1 second in the experiment.

We have tried to illustrate one possible way of this technique in the following figure.

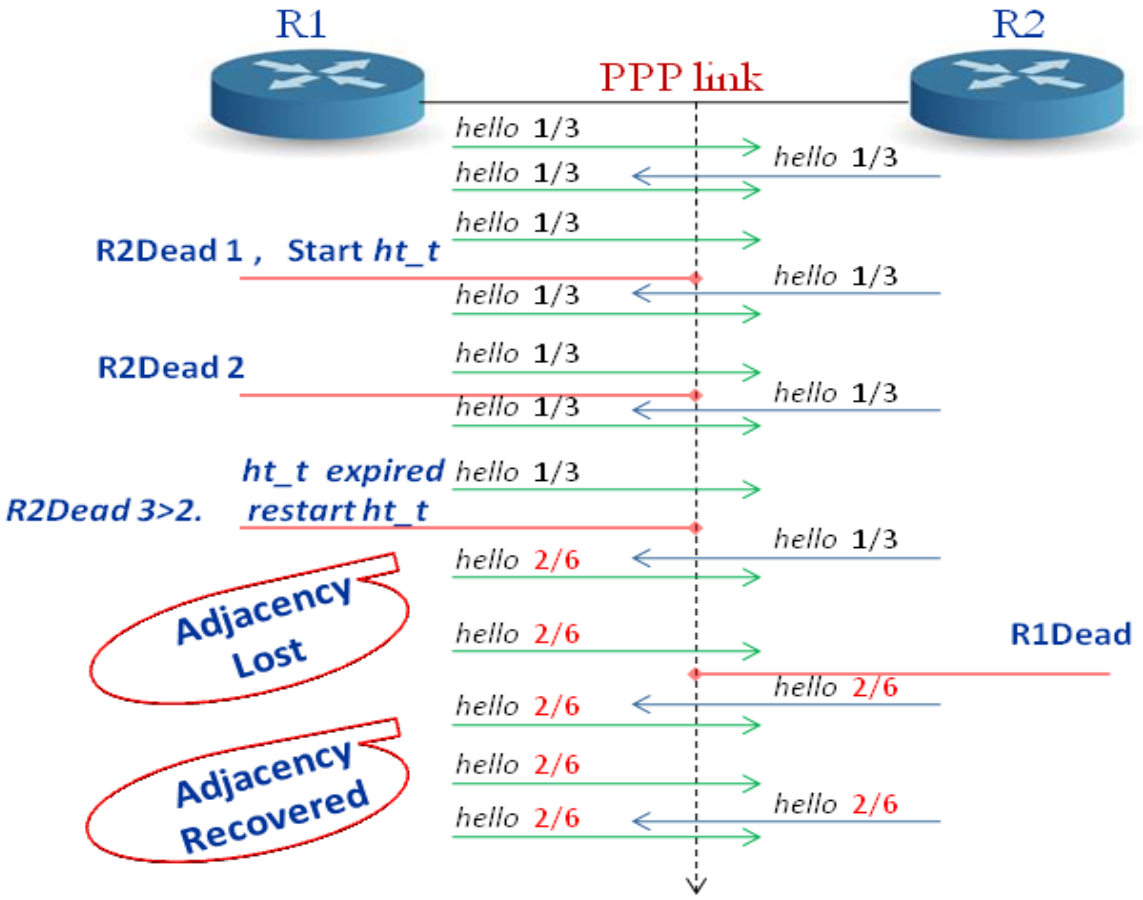


Figure 3.1: The Dynamic Hello Scheme.

Amir Siddiqi and Biswajit Nandy [36] have proposed a similar technique to mitigate route instabilities by dynamically tuning the OSPF failure threshold at times of congestion. This technique instead uses a fixed *hello* interval but varies the *routerDeadInterval* (RDI) based on the experienced network congestion level. The congestion levels are determined by monitoring the history of the number of hello packets received over a certain period of time and then determining the hello drop rate based on which the RDI values are dynamically assigned. Network interfaces are classified as master and slave based on their router ID .Only the master can changes the RDI value but the slave can propose a change when it experiences congestion. Simulation results of this technique under a highly congested network show a significant reduction in the number of adjacencies lost compared to the standard OSPF implementation.

3.2 Bidirectional Forward Detection (BFD)

Failure detection time is one of the factors that delay the convergence process as discussed in the chapter 2. In traditional OSPF implementations, this time is dictated by the *routerDeadInterval* (4**hello*). Achieving sub-second convergence using native hellos or *fastHellos* is challenging if not impossible for a simple fact that even *fastHellos* do require a minimum of 1 second to detect failure [10]. And on top of this, using fast hellos may not be a good choice for the operation highly consumes CPU cycle. The best alternative for most of the IGP implementations today is BFD (RFC5880) which is based on sub-second keep-alive timers. BFD is a light weight failure detection protocol designed to detect fault quickly in the bidirectional path of two routers including the interfaces, data links, and forwarding planes[7] [10]. It is designed to be implemented on the data plane of distributed router architecture independently of media, data and routing protocols.

Unlike point to point links that have a hardware failure detection mechanism, layer 2 technologies such as Ethernet that mainly rely on hello protocol to detect failures require fast failure detection mechanisms like BFD. BFD in its best-scenario provides comparable failure detection time as the expensive layer1/2 technologies such as packet over SONET/SDH which normally requires a few tens of milliseconds [7] [10].

3.2.1 BFD Neighbor Relationship Formation and Tear Down

BFD relies on the configured routing protocol to discover its peer. As an OSPF process discovers a neighbor, it sends a request to the BFD running locally to form a BFD neighbor relationship with the neighbor. BFD neighbors create BFD session and negotiate the time in which the control packets are sent and received to detect connectivity problems.

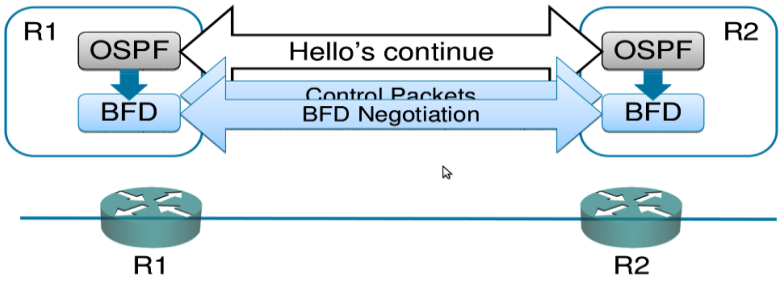


Figure 3.2: BFD neighbor relationship formation (Asynchronous mode)

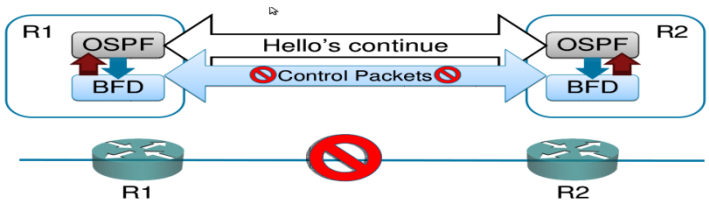


Figure 3.3: BFD Error Detection Mechanism (Asynchronous mode)

When failures occur in a network as shown in Figure 3.3, control packets are not received on both sides. As a result, the BFD session is torn down and the BFD reports to the OSPF that the neighbor is unreachable. This helps the OSPF to detect failures quickly and find an alternative path if available.

Two main modes of operation are supported by BFD, asynchronous and demand modes. The asynchronous mode is the main mode of operation that involves a periodic exchange of control packets (just like hellos). Most of Cisco's IOS systems support asynchronous mode BFD. The demand mode that works over demand circuit like ISDN does not involve a periodic exchange of BFD control packets after the BFD session is established. A short sequence of BFD packets is exchanged instead when a device needs to check connectivity explicitly and it can operate independently in each or both directions [11] [7]. BFD also support echo function that works with both asynchronous and demand modes. The echo function allows a device to send echo packet to its neighbor by setting its own address as the destination address (self-destined packets); the neighbor immediately forwards the echo packet without processing it and this reduces the round-trip time jitter. BFD echo packets are encapsulated in UDP packet and destination port 3785 and detect failures between directly connected neighbors. If the echo packets sent are not received within the BFD detection time interval then the device can declare that session is over. Since Echo function can independently provide a faster detection mechanism, the rate in which the BFD control packets are exchanged between devices can be reduced. The disadvantage of BFD is that it cannot detect failures on control plane as it is implemented on the data plane .However, it can be used with *fast hellos* to achieve that. Details about the BFD protocol can be found on RFC 5880.

3.3 Fine-Tuning Delays in LSA generation, SPF computation and Flooding

This section discusses various optimization techniques for LSA generations, SPF computations and Flooding.

3.3.1 LSA Throttling (dynamic *minLSAInterval*)

The implementation details of this technique, as part of our project, are discussed in chapter 5. Here we will brief how the technique works. Topology changes in an OSPF network are communicated using LSAs. RFC 2328 mentions the following topological changes as possible causes of LSA origination.

- An Interface's state changes(Up/Down)
- Designated Router(DR) changes(Broadcast, NBMA networks)
- Neighboring routers change to/from FULL state

In general, a change in any of the contents of an existing LSA results in a new LSA that reflects the new change. For safety reasons, the origination of any two consecutive LSAs should be at least *minLSAInterval* apart. *MinLSAInterval* (default 5s) is a router's built in mechanism to safeguard the router's CPU at times of large scale topology changes or persistent link/node flaps. However, for today's modern CPUs, this delay seems too conservative and intolerable. Instead, as argued in [7], it can be set to a smaller initial value for fast convergence to changes and made to adaptively increase with the network load. LSA throttling is one such approach to adaptively increase/decrease the LSA origination interval using exponential back off algorithm. It was introduced in Cisco IOS Release 12.2(27) SBC and documented in [12].

LSA Throttling makes use of *initial* interval, *hold*, and *max_wait* timers. If an LSA is to be generated for any of the above reasons, it will be first delayed for an *initial* amount of time, and when the initial delay timer expires, the *hold* timer starts with a given *hold* interval. Any subsequent events within the *hold* interval will not generate an LSA; instead they are accumulated until the *hold* time expires and a

single LSA is generated as a result. And, so long as the flap continues, the process also continues increasing the hold interval exponentially (2^t*_hold_) until it reaches a certain preset *max_wait* value. The hold time will no longer increase beyond the *max-wait* but maintain that value even if the flap continues. When no flap is detected within the duration of 2**max-wait* delay, the *hold* timer is reset to its initial value. It's important to note that the *hold* interval should roughly equate to the total convergence time explained in chapter 2 so that all routers would have already reflected the new change before the next comes. Cisco's default configuration uses 10 100 5000 milliseconds for these three timers respectively and recommends that the *hold* interval should be set greater than or equal to *minLSArrival* so that other routers receiving the update do not miss/drop valid LSAs.

3.3.2 SPF Throttling/SPF hold-down

Unlike modern high speed routers that take in the order of milliseconds to a few seconds to complete SPF computation [13] [14], older systems of the 1980s and 90s took tens of seconds to complete the operation. One factor for this, apart from the then smaller CPU power is the inefficiency of the original dijikstra's algorithm. The original dijikistra's algorithm with an average complexity of *nlogn (even n2 for full mesh)* is considered to be inefficient and less scalable in light of its modern variants that take an average complexity of logn [15]. However, for modern ISP networks that maintain hundreds of thousands of routes, SPF calculation has remained one of the CPU-intensive operations that need to be optimized.

RFC 2328 specifies SPF computation immediately following the reception/origination of a new LSA i.e., it was pure *LSA-driven*. If a router is scheduling SPF computation for every single LSA it receives, that might ultimately locks the CPU only for SPF computation and all other useful tasks would be stranded. A somewhat conservative approach of this uses a *fixedHoldTime* [16][17] between successive SPF computations, but that too doesn't scale well and delays convergence. *SPF throttling* is a modern SPF scheduling scheme that uses the same technique and procedure as LSA throttling but it works on delaying the SPF computation after the LSA has already been originated/received via flooding.

Three parameters namely *spf-start* interval, *spf-hold* timer and *spf-max-wait* timer are used in this technique. The *spf-hold* controls the number of SPF iteration and it should be set optimal to the convergence of the network. Likewise, *spf-start* should be kept as minimum as possible to allow for instant reaction to changes like transient faults and occasional topology changes but large enough to allow for successful flooding of the originated/received LSA before SPF starts.

Juniper's implementation of this differs a little in that it has two modes of operation namely *slow mode* and *fast mode*, and unlike Cisco's exponentially increasing *hold* period it uses a linear increment. If the number of SPF runs exceeds a preset limit called *rapid runs* within a certain check period; the SPF computation switches to *slow mode* starting the *hold-down* timer. All subsequent SPF events within the *hold-down* timer won't trigger SPF computation until the *hold-down* timer expires. The following figure illustrates Cisco's implementation of SPF throttling which recommends 10 100 500 ms. A similar pattern can be inferred for LSA throttling as well.

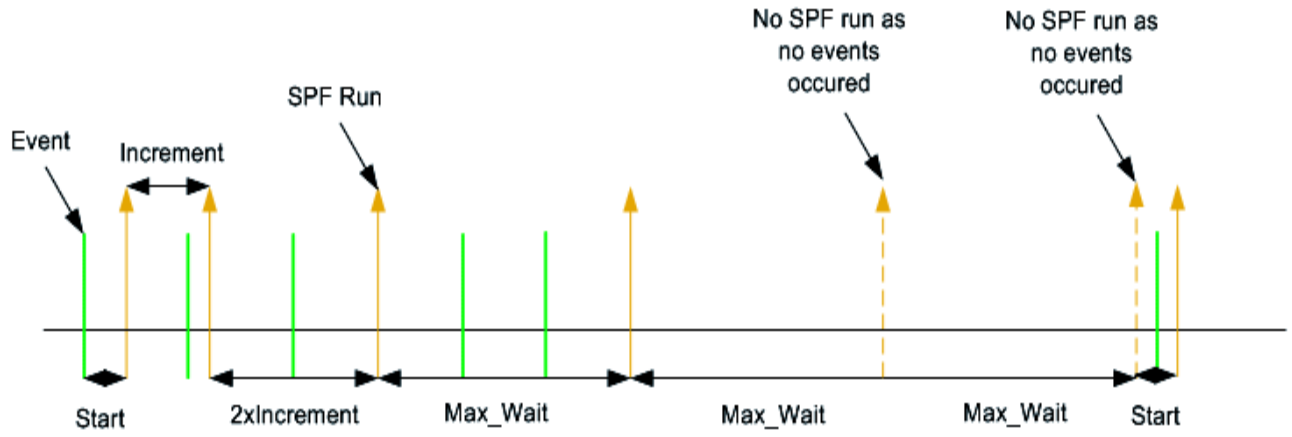


Figure 3.4: *SPF throttling* timers in action

As can be seen from the figure, at the third iteration the *spf-hold* is scheduled to 4*increment but as that exceeds the *spf-max-wait* threshold, it will be truncated to *spf-max-wait* and with the absence of flap for two more such iterations, it will be reset back to start.

3.4 OSPF *packet-pacing* delays

Cisco IOS Release 12.2(14) S have also introduced three types of OSPF *packet-pacing* delays to optimize the flooding procedure. Similar implementations also exist in junOS. *Packet-pacing* delays are used to rate limit the flooding /retransmission of LSA update packets with an intent to reduce the CPU or buffer utilization. While helping achieve fast convergence at times of occasional topology changes, these techniques instead follows a controlled flooding procedure for networks containing a large link state database (LSDB).

3.4.1 *Flood packet-pacing* timer

If a router has a large number of LSAs to be flooded out an interface one after the other, this timer dictates the rate at which this happens. The flood pacing timer is a timer set per interface and is in effect only if a router has more than one LSA.

3.4.2 *Retransmission packet-pacing* timer

As part of the OSPF's reliable transmission, all LSAs sent to a neighbor are kept in a retransmission list for later retransmission in the absence of acknowledgment. Retransmission packet-pacing timer works in the same way as the flood pacing timer by controlling the rate at which LSAs are sent from the retransmission queue. A more advanced implementation of the retransmission timers, as suggested in RFC 4222[18], is to have a dynamic *RxmtInterval* just like the dynamic *minLSAInterval* technique discussed in section 3.3.1 so that *RxmtInterval* exponentially increases whenever the number of unacknowledged packets in the retransmission list rises above a given threshold (e.g. at times of congestion).The interval is again reset to its initial values when no sign of congestion is detected.

3.4.3 *Group packet-pacing* timer

Prior to this feature, Cisco's OSPF implementation [19] used to have a fixed 30 minute refresh interval after which all the self-generated LSAs of a router are refreshed. The refresh applies to all such LSAs at a time despite their current respective ages. Such a schedule creates a periodic spike of LSAs flooded to the network and that would require a considerable amount of CPU processing and buffer utilization.

The OSPFv2 specification according to RFC 2328 instead applies an individual refresh time for each self-generated LSAs so that an LSA is flooded when it hits its 30 minute limit (which is its *half-age*). This on the other hand makes the flooding more frequent and inconvenient. A more recent implementation of Cisco adds a delay called group pacing delay (default 240ms) to each refresh times in an attempt to contain several LSAs into a single LSA update packet. This would make the flooding more efficient and reduce the load on the sender as well as on the receiving neighbors, but this somehow delays the convergence process. Details can be found in [7] [20].

3.5 IP Event Dampening

IP event Dampening or BGP dampening (for BGP, rfc2439) is also a widely used technique to ensure global routing stability by reducing the effect of route flaps which are caused by high-frequency interface/link flaps. Almost all routing solutions of Cisco [21] since IOS release 12.0(22) S and junOS's BGP implementation [22] include this feature in their distributions. We will brief Cisco's implementation of this below.

Cisco's IGP implementation of this is used to punish a persistently flapping interface by hiding its state transitions(UP/Down) from upper layer protocols and hence from the network. This helps to temporarily shut down the link and freeze all routes through it until it stabilizes. This technique is very similar in effect with LSA throttling but is a bit conservative and may not be enabled if a router is already using LSA throttling or the other way round. Every time an interface flaps (goes down), it is assigned a penalty value according to the formula Pn =**Pn-1*2^ (-t/H) +Pn-1.** If this accumulated penalty value exceeds a maximum threshold value called the suppress threshold, the interface is suppressed. It'll be unsuppressed when the penalty drops below the re-use value.

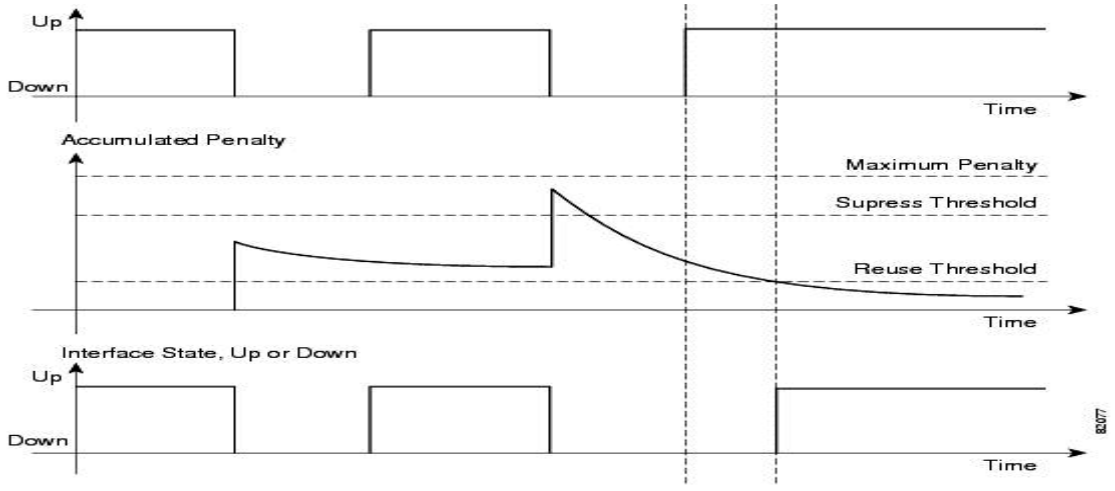


Figure 3.5: IP Event Dampening [21]

The algorithm makes use of the five parameters; *penalty* (*figure of merit* as junOS calls it), *suppress/cut-off* threshold, *half-life* period, *reuses* threshold and *max- suppress* time. The explanation follows the definitions of these parameters.

Suppress threshold (default 2000) - Is the maximum accumulated penalty value after which the link is suppressed. If the penalty counter is >1 in the *half-life* period, the penalty keeps on increasing by P***2^ (-t/H) + P.**

With the absence of flap in every *half-life* period**,** the penalty follows exponential decay according to the formula **P(t)=P(0)*2^(-t/H);** whereas if the flap counter is >1 in the *half-life* period ,the penalty keeps on increasing by **P*2^(-t/H)+P .**

P (t) stands for the *penalty* (initially 1000) at time **t** and **H for** the *half-life* period defined below.

Half-life period (5s) - Is the duration of time after which the penalty is exponentially decayed according to the above formula (determines how fast the penalty decreases exponentially).This time has to be carefully chosen based on the frequency of the flap. Generally, the derivation from the above formula holds **H >= T/log2 (P/(S-P)**.

Reuse Threshold (default 1000) - Is the lower limit of *penalty*. If the *penalty* value falls below this value, the interface is unsuppressed/ reused.

Max-suppress-time* (default 4*half-life*) **-** Refers to the maximum time a route can be suppressed. It's recommended to have this feature deployed specially on networks with redundant links, which are typical of large service providers, due to the fact that routers start to use an alternative link stably until the flapping link settles.

3.6 SPF enhancements

3.6.1 Incremental SPF (iSPF)

SPF computation using the old Dijkstra's algorithm, aka *static dijkistra* [23] is now believed to be inefficient in many aspects. One of these limitations is that a full SPF computation is undergone over all LSAs in the LSDB for every new LSA received. Nevertheless, it may be the case that such an LSA won't affect/change the existing Shortest Path Tree (SPT) tree or it may only changes part of it.

This happens for example, when the LSA describes the failure of a link which is not part of the saved SPT (every new SPT has to be saved for iSPF). Such topology changes should simply be ignored if identified properly.

iSPF is a more sophisticated approach that avoids such unnecessary computations by carefully examining the newly arriving LSAs against the saved SPT before triggering a new SPF. iSPF also enables fast RIB updates [23] by avoiding redundant RIB updates and this contributes a lot for the convergence speed.

The feature is available in Cisco IOS Release 12.0(24) S and later. Please refer the description following figure 3.6 for this and some more properties of iSPF.

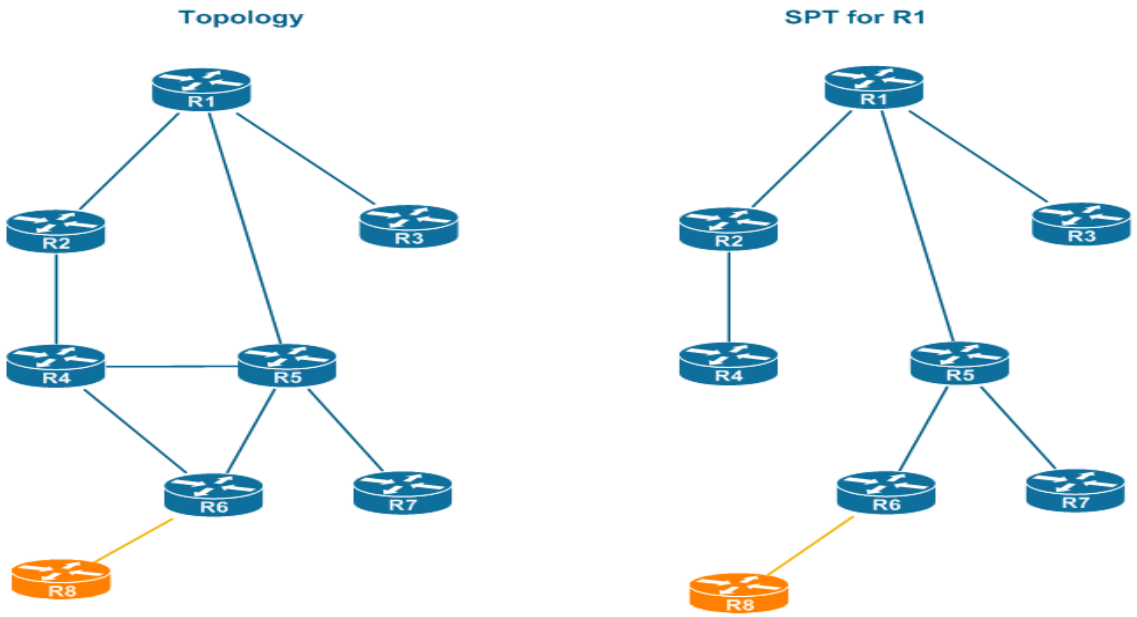


Figure 3.6: Sample Topology (left) and spanning tree (right)

property1. If the topology change is the addition of new leaf node like node R8 in the fig above, simply extend the SPT from R6 and its cost would be the cost to R6 plus the interface output cost to R8. This property is similar to the partial route computation discussed in section 3.6.2.

Property2. If a link that wasn't previously in the saved SPT, say R4-R5 is down, and then this wouldn't trigger a new SPF.

Property3. If any link in the current SPT tree fails say the link between R1 and R5, then that would trigger an SPF computation from the root to R5, R6, R7 and R8; that is to all the nodes in the sub tree of the failed link.

iSPF proves more effective on topologies with fewer number of interconnections (less dense) and the farther away the failure is from the root ,the simpler would the computation be and this compensates for the longer propagation delay resulting from such distant failures.

3.6.2 Partial Route Computation (PRC) in ISIS

As pointed in the previous section, OSPFv2's inherent way of handling information in its LSAs has some inconvenience when it comes to PRC. IP prefix information (the connected subnet information) is an integral part of an OSPF type 1 or type 2 LSAs which also carries topology information. So whenever an IP prefix or the status of a stub link changes in the area, the same LSAs are generated like for any other topology change that must trigger SPF. OSPF has no way to identify that such changes are only of IP prefix and not of topology, as a result of which it schedules a normal full SPF. Should it detect such changes, only PRC over the changed prefixes will be computed which is way far simpler task to do. But OSPF does so only for type3 and type5 LSAs both of which carry IP prefix information for external routes.

PRC is an integral part of ISIS due to the fact that ISIS's handling of information in its LSP is more suited to such optimizations. It has a separate TLV (*Type-Length-Value*) to carry the IP reachability information and another one for IS (Intermediate System) Neighbors information (i.e. topology information) out of which the SPF is computed independent of IP prefix information. Every IP network in ISIS is considered as external and end up being a leaf; so whenever a stub link or a leaf node is added/removed, ISIS does PRC just like a distance vector addition/removal and only transient link failures that might potentially affect the whole topology do trigger a full SPT. That said, major vendors like Cisco have managed to find a way out to this problem in OSPFv2 also, in such a way when leaf nodes are added/removed from the network, the routes are redistributed just like type3 or type5 LSAs instead of the normal case where they are advertised as type 1/2 LSAs. This trick has enabled OSPF to do PRC on stub/leaf links, with a little more associated CPU overhead. However with the introduction of iSPF to both OSPF and IS-IS this is no longer an issue. Please consult [18] for more and associated issues on this and [25] for more explanation and difference between OSPF and ISIS.

3.6.3 Partial Route Computation (PRC) in OSPFv3

OSPFv3 for IPv6 does this in a more smarter way by introducing a new type 9 LSA called an intra-area prefix LSA that carries a separate intra-area network prefix information[26] (with no IP addressing semantics). Router /Network LSAs are carried in separate LSAs that carry only topology information.

In OSPFv3, LSA identifiers such as router Ids, Area Ids and Link-state Ids are all 32 bit numbers written in dotted decimal representation but they are not actually IPv4 addresses but just numbers. These numbers uniquely identifies each router in a given area; unlike OSPFv2 which identifies neighbors by their interface IP addresses (BR and NBMA networks) or an IPV4 router Ids (point to point and other).

Type1 or Type2 LSAs do not carry IP addressing semantics information and are only transmitted when information pertinent to SPF calculation exists. Otherwise simple IP prefix or stub link changes only generate intra-area-prefix LSAs for which SPF would not run. This has made it easy to modify IP prefix information without affecting SPT tree. Consult OSPFv3 RFC 5340[26].

3.7 LSA Correlation

LSA correlation is another SPF optimization technique proposed by the authors in [27].The authors believe that the hold-time based SPF calculation that uses fixed/exponential back off algorithm has unnecessary delays and is inefficient in some circumstances. They argue that individual LSAs are only symptoms of a topology change and should not always trigger SPF computation. Instead, each received link states in the update packets need to be collected over a period of time and correlated for possible topology changes. The correlation process identifies possible similarities between link states over adjacencies by thoroughly inspecting mainly the *link ID, link Data,* and *link Type* fields of the LSA. And if any topology change is noticed during the correlation process that will immediately trigger SPF calculation. The idea seems smart on one hand due to the fact that LSAs describing the same change could be generated by multiple routers adjacent to each other, each of which possibly requiring SPF runs when received by a destination.

Part of the processing in LSA Correlation is of course already specified in RFC 2328 and the authors have noted that. The RFC clearly states that every received LSA should be checked for changes against the previously stored LSAs unless it is the first time it is received, and SPF computation is scheduled if and only if there is a difference in topology. However, as to our observation and the authors claim, the original OSPFv2 specification doesn't differentiate similarities over adjacencies.

In the simplest case, when a link between two adjacent routers in a point to point network fails, both the routers generate an LSA describing the change. A router receiving these LSAs possibly over a period of time may schedule SPF for each despite the fact that they talk about the same thing. To give another example, suppose a central node that carries multiple adjacencies in point to point network crashes, as a result of which each of the adjacent routers generate an LSA describing this. Suppose a distant router receiving each of these LSAs. The traditional implementation might schedule SPF for each LSA it receives. The question is can we make this smarter? The author's claim this can be made smarter if the receiving router could somehow analyzed the nature of the link states in these LSAs. For the first received LSA, it immediately schedules SPF (to reflect changes immediately, considering it as an occasional topology change) but if a second LSAs is received from a different router announcing the loss of adjacency with the same central node , then this might be a sign that the central router is going down, so it waits for a while before running SPF hoping to see more such announcements from the remaining adjacent routers also(its assumed that the calculating router keeps track of all adjacency information of a router through their router's LSAs) and once it makes sure that it has got hold of all the LSAs from all adjacent routers ,it schedules an SPF (the second SPF) . This is in contrary to the pure LSA driven /fixed hold-time or an exponential bakeoff scheme which requires more SPF runs may be one for each such instance in the worst case. Further details including the pseudo code are found in [27] [23].

The three main steps in LSA Correlation are:

Step 1: Identify an up, down or cost change sub-event by carefully examining the contents of the new LSA and its saved version.

Step 2: Correlate the sub-events to identify a topology change.

Step 3: Post processing following the topology change.

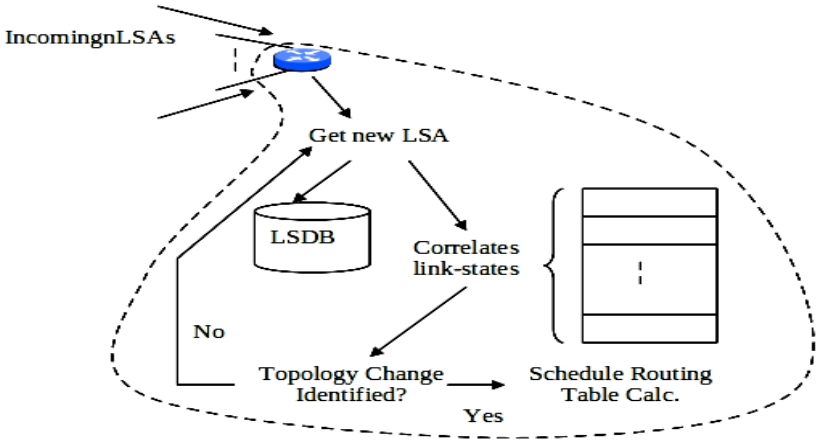


Figure 3.7: The overall LSA correlation procedure [35]

3.8 Graceful Restart (supported by both Cisco IOS and JunOS)

At times, it may necessitate that a router be down temporarily as part of a planned maintenance/upgrade activity or due to unplanned events such as power cut or crash. Nevertheless, an operator may still demand that the existing network communication should not be disrupted in the meantime. This need can be addressed by a procedure called *graceful restart or non-stop forwarding*, as documented in RFC 3623[28] [7]. Graceful restart makes use of the separate architecture of the control and the data planes of modern routers. This distributed architecture has given a rise to the possibility that the control plane, which takes care of all the OSPF operations, be restarted safely leaving the data forwarding operation to the forwarding plane/data Plane. The procedure goes as follows.

The restarting router called the *initiating router* sends a special message called *grace LSA* which is a link local Opaque LSA to all its adjacent neighbors called *helpers* before it restarts (it does so after it restarted before sending hellos, for unplanned reboots). The grace LSA is not to be flooded by the helpers but is just a signal that the initiator is restarting so that the helpers should not break their adjacency but instead pretend that the router is still up and continue advertising it in their LSA. The initiator has to flush the grace LSA after a successful restart. In the meantime, the helpers enter in to a *helping mode*.

In order to avoid possible mismatch, the initiating router saves its sequence number in a non-volatile memory before it restarts and when it restarts, it re-introduces itself by re-originating its router/network LSA, re-rerunning SPF and updating its forwarding table (it has to flush the grace LSA before this). However, should any topology change occur during the restart period, the initiator couldn't reflect this change in its forwarding table and that may potentially create a routing loop. In such cases, its helpers would no longer hide its restart and break their adjacency (exit the helping mode) by omitting the adjacent link from their LSAs. This time, both the initiator and its helpers assume a normal restart and this is of course unwanted. For planned reboots, the network administrator has to issue the appropriate command along with an estimated grace period which should normally be less than 1800s (in order to avoid the LSAs being aged out during the restart period). Graceful restart is not recommend at times of unplanned reboots due to that fact that the router would not have enough time to prepare for it and this option should normally be disabled by default, more on the RFC [28].

3.9 Incremental FIB Updates

FIB update times vary between routers depending on the nature of the failure and depending on the number of routing prefixes affected by the failure. As experimental results show in [14] [13], FIB update time contributes the most to the convergence delay. Recent improvements [29] suggest a technique called incremental FIB update (iFIB). This technique, instead of dumping the whole routing table on the line cards whenever a topology changes, it rather selectively updates only the routes or the prefixes affected by the change. This approach works best with iSPF technique discussed in section 3.6.1 and is proved to significantly reduce the convergence time as well as saves bandwidth.

4. Sub-second convergence and the associated challenges

OSPF has a better convergence time than a distance vector routing protocol like RIP. As mentioned in chapter 3, a convergence speed can be affected by different factors. Today there is a high demand for a sub-second convergence speed in a network, but the associated challenges of CPU utilization and the network instability that can result need to be addressed as well. It is common to see 10 gigabit link between two devices in core networks of services providers'. The failure of such links for a few seconds can result in loss of information before the network fully converges, and it can impact customers' service. Here are some of the main reasons why sub-second convergence is very crucial.

- The high importance of services uptime
- The wide spread deployment of real time applications such as VOIP
- Deployment of PWS like the Earthquake and Tsunami warning system (ETWS) as well as
- Real-time mission and critical applications, from controls that are being used in industry to different sophisticated battlefield communication systems.

As mentioned in chapter 2, network convergence time is the sum of the durations that takes to detect failures, propagate the event, perform SPF calculation and update the RIB/FIB on each router. To achieve a sub-second convergence, each step involved in the convergence process need to be completed in milliseconds. Fast reaction to a perturbed network environments can lead to a network that will not converge for certain period of time. While trying to achieve fast convergence, network instability can be introduced on the other hand. Depending on how frequent the network component's status flaps, an excessive reaction by the underlying network's protocol in some troubled environment can consume high CPU and bandwidth, which even can have the potential to melt down the whole network. As a result, stability is a key property of a recovery mechanism that needs to be addressed in fast convergence.

In disturbed environments stability of a network can be maintained through controlling the way a network recovery mechanism reacts up on changes. Dampening techniques that can be implemented at different layers in a network are the basic methods to maintain stability in perturbed network conditions. Interface dampening using an exponential decay algorithm and exponential back-off algorithm both in LSA generation and SPF computations are some of the important techniques available. Large convergence time, high routing load on routers and many route flaps within short period of times can be taken as indicators for instability in a network.

4.1 Suggested methods to achieve fast failure detection mechanisms

As mentioned in the previous chapters, fast convergence is achieved through a quick discovery of failures in a network. Sub-second error detection mechanism is one of the requirements to achieve sub-second convergence. A quick discovery of failures in a network can be achieved using a reduced *hello* timer, or more preferably using hardware based techniques and BFD.

A). A reduced *hello* timer

A reduced hello timer, reducing the *hello* timer notably improves the time to detect failures between nodes, but it will also increase the load on every router as they are required to process the fast *hello* packets. It is possible to reduce the *hello* interval to millisecond ranges but the impact on CPU and network stability need to be taken in to consideration. CPU utilization in routers can increase for the following reasons.

- As routers process hundreds of neighbors' *fastHello* packets
- As multiple concurrent failures and/or recoveries occurs
- As LSA storms occurs in a network and so on.

As OSPF reacts quickly to a continuous flaps in network that are close in time, several routes on a routing table can be removed and added back within a short period of time, this is characterized as route flaps. Route flaps caused by link flaps, in a perturbed OSPF network, always lead to a network instability and unreliability [8]. Using a real ISP network model (292 nodes and 765 links) Anindya Basu and Jon G. Riecke [9] observed a six-fold increase in the number of route flaps when reducing the *hello* timer from 500 ms to 250 ms. They suggested the value 275ms as the optimal one. The authors in [7] however suggest 500 ms as the optimal *hello* timer value with its failure detection time capability of around 2 seconds.

In [15] it is stated that the *hello* timer is dependent on the physical constraint of links, like the link noise hits. The authors in [30] tried to determine the optimal *hello* interval for a network. They suggested that the optimal *hello* timer depends on the network's expected congestion level and the number of links in the network topology [30]; the authors in [7] also agree with these suggestions and point out the network's tolerance for false alarm as an additional factor.

The authors in [8] showed in their simulation network that fast detection, using an optimal *hello* timer, is achievable under stable network. However, under unstable condition the dynamic *hello* timer (see chapter 3) grows exponentially affecting the detection time and convergence speed but relatively reducing the consumption of the CPU and bandwidth. It provides a more tolerant mechanism to frequent network changes.

B). Hardware based techniques

Hardware based techniques can discover failures in tens of milliseconds but it may not be always available either due to the network type or the cost involved. A point to point gigabit link can detect failures between two nodes almost instantly, using a network pulse.

C). BFD

BFD in its best-scenario can help achieve 50ms error detection mechanism [7]. To detect failures in forwarding planes, BFD is preferable over sub-second *hellos* both in terms of its quick detection and its routing load. It can be used in conjunction with *fastHello* to minimize detection time in control plane.

Finding an optimal *hello* timer that avoids false alarms and extra processing in a network is not an easy task, as mentioned above. Quick failure detection mechanisms alone in a perturbed network environments can lead to instabilities e.g. link flaps causing route flaps, and it can be prevented using the dynamic *hello* timer techniques. The IP event dampening techniques(see chapter 3) can also be used to damp some oscillating router interfaces in order to achieve a more stable system. Therefore, BFD can be used with the IP event dampening techniques to restrain any possible flapping interfaces.

4.2 OSPF enhancements to optimize event propagation

Being one of the factors that determine the convergence process, the event propagation technique requires an optimization to achieve fast convergence and at the same time a more stable network. The event propagation can be affected due several factors, as mention in chapter 2. Among the factors, the LSA storm results in high CPU and memory utilization at a router. This makes incoming packets to be delayed or dropped, especially where *fastHello* is used. Packets being missed or delayed can result on adjacency breakdown or an increase in the LSA retransmission rate that further can put the network to unstable state.

In [18] the current "Best Current Practices" for OSPFv2 fast convergence are discussed. The following methods have been stated as good practices to improve the scalability and stability of large OSPF networks:-

1. Assigning high priority to *hello* packets and link state acknowledgment packets and low priority to the others.
2. Reset the inactivity timers for an adjacency upon receiving any OSPF unicast packets or packets sent to *AllSPFRouters* over point-to-point link instead of waiting for the hello packet only. Adjacency is declared down only on the absences of these packets over the period of *RouterDeadInterval.*
3. Use an exponential back-off algorithm to determine the rate at which the LSA be retransmitted (*RxmtInterval).*This helps in reducing the rate of LSA retransmission as network experience congestion.
4. Implicit Congestion Detection of neighbor routers and taking action using exponential back-off mechanisms. The detection is done using the level of unacknowledged LSA packets. If the level passes certain "high-water mark", the rate at which LSAs are sent to the neighbor router is reduced using exponential back off mechanism to some minimum rate. The rate is increased again exponentially as number of unacknowledged LSAs to the router reaches certain "low-water mark". Both 3 and 4 helps avoid excessive congestion at a neighbor, the difference is that 3 is only for retransmission but 4 works both for new and retransmission of LSAs.
5. Reducing the number of adjacencies to be brought up simultaneously, since sending large number of adjacencies to neighbors can cause severe congestion due to database synchronizations and LSA flooding activities. Here, only "n" number of adjacencies can be brought up at once. The value"n", which is configurable, is based on the processing capability of routers, total bandwidth available for control plane traffic and propagation delay.

In addition to the different methods mentioned above, the following are some of the important available enhancements that optimize the event propagation process in an OSPF network.

6. An LSA throttling technique that takes network convergence and stability into consideration (See chapter.3).
7. Group pacing delay that is available in commercial routers, LSAs are grouped to refresh together so as to reduce the number of LS update packets and prevent LSA storms (See, chapter 3).
8. Setting the *DoNotAge* bit in LSAs to avoid periodic refresh, this significantly reduce the LSA processing overhead of routers [31]. Routers flood their self-originated LSAs with the *DoNotAge* bit set, this reduce the protocol traffic overload in stable network. No need of re-flooding self-originated LSAs every 30 minutes, the re-flooding interval is extended to configured forced-flooding interval. New instances are originated up on LSA changes by the LSA originator.

4.3 Optimization in routing table calculations

Being one of the factors that determine the convergence process, routing table calculation requires an optimization. Below are some of the important techniques that can be used to improve the routing table calculation process.

Mechanisms	Description	Pros/cons
Fixed hold time	It is a fixed delay that is enforced between successive SPF calculations.	Prevent too many routing table calculations after topology change. Affect the convergence duration but good for routing stability.
SPF throttling, with quite period(Cisco)	Initially small hold time, but receiving one or more LSAs within the period of hold time double the next hold time until certain maximum value. The hold time is reset to small value if no LSA is received after 2**Max_hold* , see chapter 3	Helps achieve fast convergence duration. Tries to keep the network stability at times of network disturbance that may result in several SPF calculations.
Juniper scheme	The first few SPF calculations are done with small values (fast mode operation), if too many SPF within certain threshold, it goes to large hold time (slow mode). If no LSA is received during the large hold time it is reset back to a small value.	Changes with few routing table calculation result in fast convergence but affect the frequency of the SPF calculation for large scale topology changes.
LSA correlation	Tries to identify the underlying topology change by correlating the LSAs.(See chapter 3)	Fast convergence with reduced number of SPF calculations.
iSPF	Avoids unnecessary SPF computations by examining newly arriving LSAs against the saved SPT. (See chapter 3)	Contributes to convergence speed, since it enables fast RIB updates.
PRC	Involves partial route calculations over changed prefixes. (See chapter 3)	Improves the convergence speed.

Table 4.1: Optimization in routing table calculations

4.4 Optimization in FIB updates

iFIB is used to optimize the FIB update time, it works best with iSPF (see chapter 3).

4.5 Achieving Sub-second convergence in large IP network

In [13] the authors have showed that it is possible to achieve sub-second convergence in large scale network (Tier-1 ISP network model with 200 routers in Europe, America & Asia) without affecting the stability of the network. Their simulation study was performed using ISIS, which equally applies to OSPF. The simulation experiment contains the following assumptions and conservative approaches

- Packet over SDH (Synchronous Digital Hierarchy/SONET (or POS) links in SP backbones or BFD as means of sub second error detection mechanism.
- Dynamic timers in LSA generation and SPF computations.
- 40 G link speed, no pacing timer
- iSPF and iFIB
- prefix prioritizations

Using the experience from this survey and the simulation experiment in this project, we believe that using a combination of the following techniques at the different stages of the convergence process enables to achieve a fast convergence without impacting the network stability.

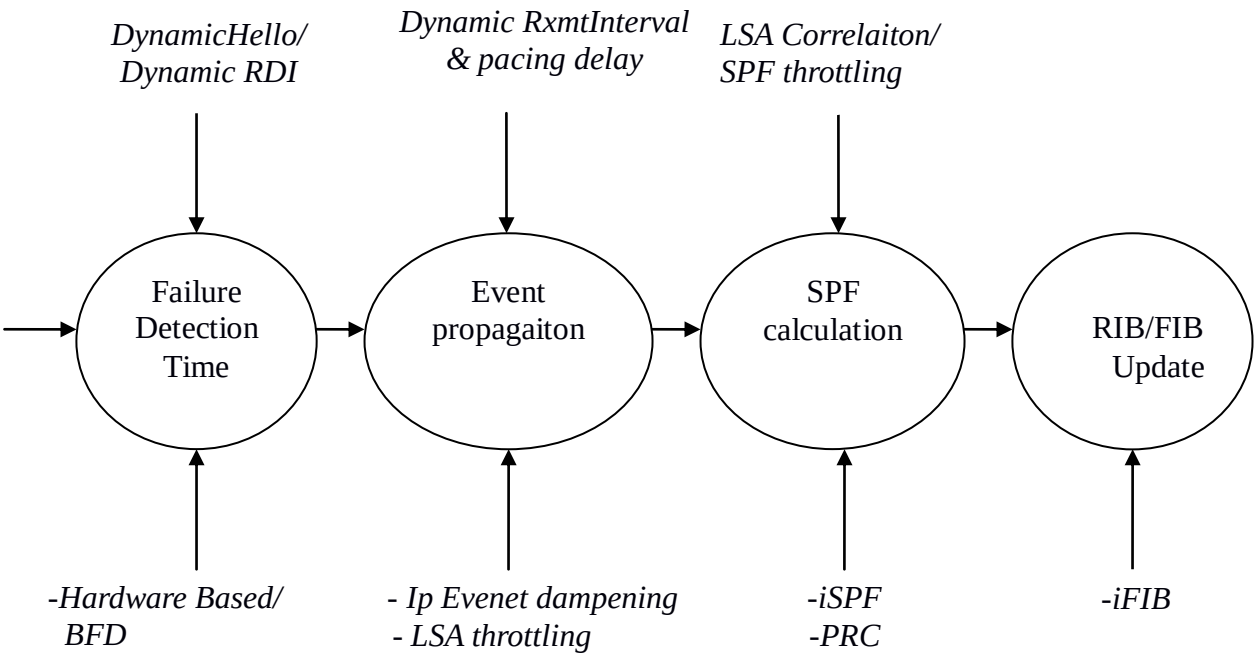


Figure 4.1: Techniques to achieve fast convergence in OSPF

5. Simulations

This chapter starts with a brief overview of network simulation and then discusses the implementation on the selected simulation.

5.1 Overview of Network Simulators

Before we started the simulation work, we had to make some survey to select a simulator suitable for the implementation. Our targets were freely available tools with modifiable OSPFv2 source code and also with a good GUI support. However finding one such ideal tool was difficult in the open source world. The commercial tools we suggested were very expensive and there was no budget allocated to buy one. NS3, OPNET IT Guru, QualNet, and OMNETPP, all of which are discrete event simulators with C/C++ development environment were among the candidates. Ultimately, we managed to choose OPNET Modeler Education version 14.5 simulator, one of the OPNET's families of solutions for its advanced GUI and support for simulation statistics related to many of the important properties of OSPF such as convergence time. These advanced features are not available in OPNET IT Guru, the other academic version by OPNET. We also used OMNET++ version 2.2.1 for its free and extendible OSPFv2 source code using which we implemented the LSA generation delay feature. We will present a brief overview of the candidate simulators followed by the experiments done on the selected tools. Detail explanations can be found in the surveys [32] and [33].

5.1.1 Network Simulator-3 (NS-3)

NS-3 is a discrete-event network simulator/emulator widely used for educational and research purposes. It's a relatively new tool (first release 2008) designed to improve some of the inherent limitations of NS-2 and other prior tools. It is not an update of NS-2 simulator although it makes use of many of its models, nor is it backward compatibility with NS-2; it's rather a different tool with an entirely C++ development environment and an optional python support for scripting. NS-2 uses C++ for development but scripting must be done in OTcl (Object-oriented Tool command languages) language. NS-3 provides a limited GUI support via NetAnim like NS-2 but newer tools such as PyViz and NS3-Viz are also recent introductions. The drawback with this tool is that it doesn't have an official OSPFv2 source code release but a user contributed one in the NS-3 experimental repositories with lots of unresolved issues. We didn't dare to use this tool due to such uncertainties and also due to the complexity of NS-3 simulation environment added to the poor GUI support.

5.1.2 OPNET/QualNet

The other set of simulators we considered were products of OPNET (Optimized Network Engineering Tools) Technologies and QualNet both of which are commercial closed source tools. The versions shipped with the extendable source code are very expensive. QualNet doesn't have a free version and we didn't need to investigate it further. OPNET solutions on the other hand have educational versions one of which is OPNET IT Guru. IT Guru is mainly designed for small scale network simulations with some limitations on simulation parameters such as the number of nodes. OPNET families are best for their sophisticated data analysis features and nicely designed GUI. OPNET Modeler is another educational tool by OPNET that we considered for our study. We will briefly describe OPNET Modeler and discuss what we achieved on it below.

5.1.3 OPNET Modeler

The OPNET modeler is powerful simulation tool for building protocols and device models. In addition, its GUI makes it easy to build a large size network within short period of time .Using OPNET it is possible to build up networks that run different types of routing protocols. OPNET Modeler educational version has the following key differentiating features; these are:

- Systems specified in OPNET Modeler consist of objects, each with configurable sets of attributes.
- Models are entered via graphical editors
- Automatic generation of simulations
- Application-specific statistics that can be collected automatically during simulations.
- Scalable simulation environment including support for parallel and distributed simulation

5.1.4 Simulations on OPNET Modeler

In this simulation, we have used terms like *fastHello* and *normalHello*. The *fastHello* represents a *hello* interval of one second and four seconds of *routerDeadInterval*. The *normalHello* represents the traditional *hello* interval of 10 seconds.

The simulated topology in OPNET Modeler is shown in figure 5.1; it is slightly different from the one used in OMNETPP and that was deliberately done to achieve the desired results. It consists of 24 nodes with 49 point to point links, 98 routes each.

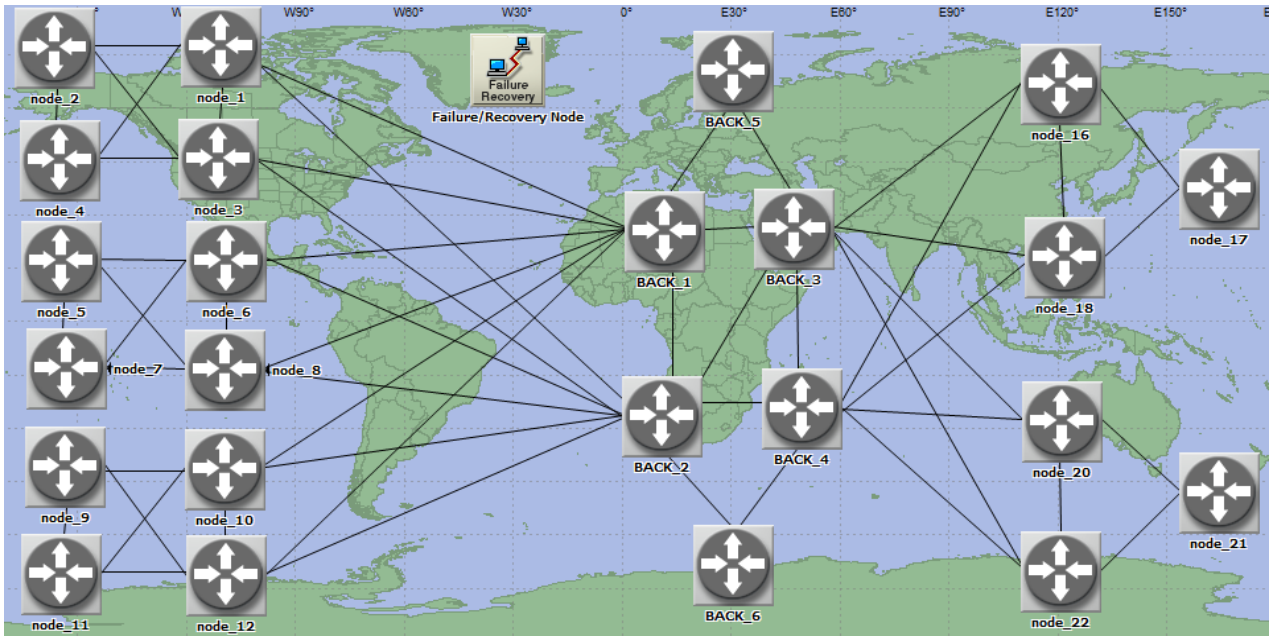


Figure 5.1: Simulated topology in OPNET Modeler

Not all the timer types in OSPF are configurable in Modeler, for example the *minLSAInterval/Arrival* parameters are fixed as specified by the RFC 2328. So, the only interesting timers apart from the

retransmission timers that we were able to make use of are the *hello* timers and the SPF delay/hold timers (with a fixed hold value).We will discuss below what values we chose, why we chose and how they influence the convergence and stability of the network below.

The network components used in the simulation experiments are slip8_gtwy_690_upgrade generic routers, a PPP_SONET_OC48 point-to-point cable with a data rate of 2488.32 Mbps and a controller node to model the failure-recovery scenarios. All the simulations in OPNET as well as OMNET assume a single area OSPF network with point-to-point links. The point-to-point network was chosen to analyze the convergence and stability issues of an OSPF network in its simplest form. This simulation work mainly tries to answer the following questions related to OSPF fast convergence and stability.

1. What effect does reducing the hello interval from 10 to 1 second has on the convergence speed and CPU utilization?
2. How the CPU utilization and convergence duration vary between *fastHello* and *normalHello* under the presence of continuous node failure/recovery?
3. What impact does concurrently failing nodes bear on the CPU utilization?
4. How do SPF parameters (initial delay and hold values) affect the stability of routes in a router?

In the OPNET Modeler the convergence speed of a router can be measured using the convergence duration. The convergence duration is the time elapsed since a first sign of convergence activity occurs (initially, or with each new disturbance) until the sign of convergence activity occurs that is followed by a certain interval of no convergence activity. In this case, we take a sign of convergence activity to mean a re-computation of the OSPF routing table. This duration is represented by a Y-axis value in the convergence duration graph.

1.) The first part in this simulation experiment shows the comparison of the CPU usage and the convergence duration between *fastHello* and *normalHello*. We observed this on a selected reference node NODE_1 in three different scenarios shown in Figure 5.2 and 5.3. The first scenario assumes a failure of a selected node BACK_3 at simulation time 100; the second assumes a delayed recovery of the failed node at time 200.This helps us to isolate the effects of a failure and a recovery. In the third scenario, the selected node is failed at time 300 and recovered at time 320; i.e. within a duration of less than 40 seconds which is the *routerDeadInterval* for the normal hellos. This is made to assume a brief restart in between 4 and 40 seconds for which the *fastHello* and *normalHello* react differently. The SPF style used was periodic with a value 1 and that was made to keep the CPU as busy as possible under the presence of continuous LSA arrivals.

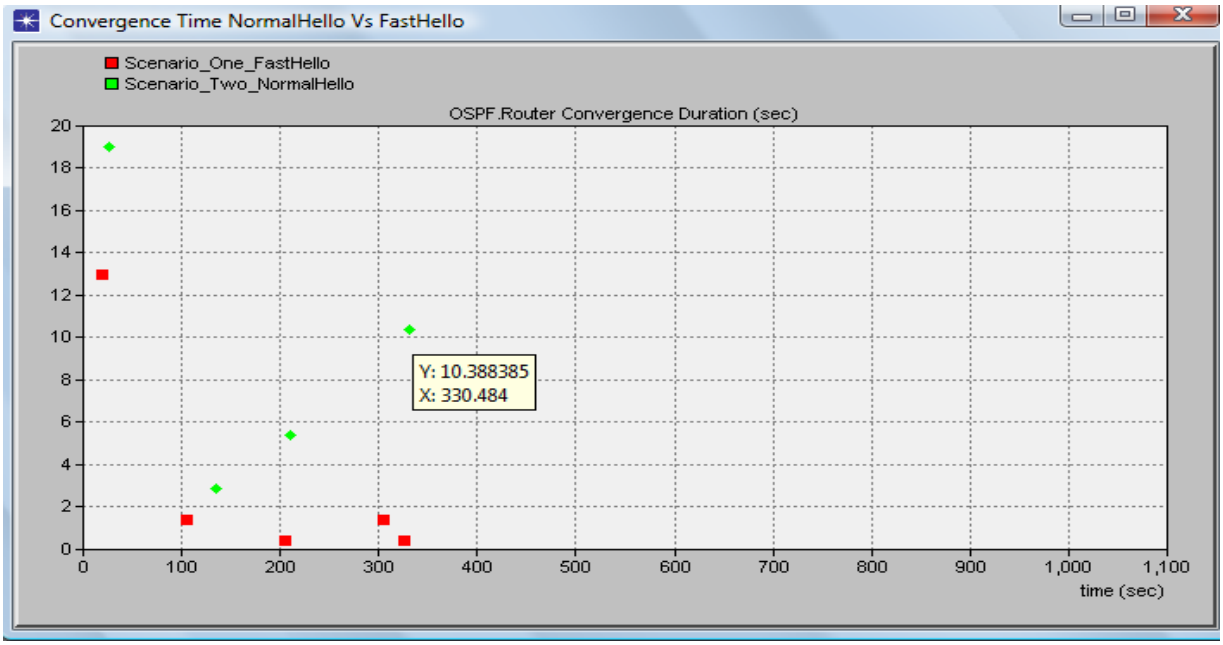


Figure 5.2: Convergence duration between fast and normal hellos

	Initial Convergence	BACK_3 Failure (100 sec)	BACK_3 Recover (200 sec)	BACK_3 Failure (300 sec)	BACK_3 Recover (320 sec)
fastHello	Y: 13, X: 19.48	Y: 1.43, X: 104.48	Y: 0.44 , X: 205.48	Y: 1.40 , X: 304.48	Y: 0.44, X: 325.48
normalHello	Y: 19, X: 25.48	Y: 2.91, X: 134.48	Y: 5.42, X: 210.48	Y: 10.39 , X: 330.48	

Table 5.1: Convergence duration(y-value) values corresponding to simulation time(x-value)

As can be seen from the above table, the convergence duration(y-value) is generally small for *fastHello* case due to the obvious fast failure detection and recovery. The other interesting point is that the fast hello scheme updates its routing table twice for the third scenario and that is due to the firing of the inactivity timer within the brief restart period and a new routing table computation is done assuming the neighbor is dead. The *normalHello* scheme on the other hand does a single routing table computation and hence has only one convergence duration. That was because the failure was not detected in less than the *routerDeadInterval*. The corresponding CPU utilization at these points is shown in Figure 5.3. The CPU rises up twice for the *fastHello* case corresponding to the number of convergence durations. From this we can conclude that while fast hello helps achieve fast convergence, it may not be that effective in terms of CPU utilization if there are continuous but brief restarts in a network.

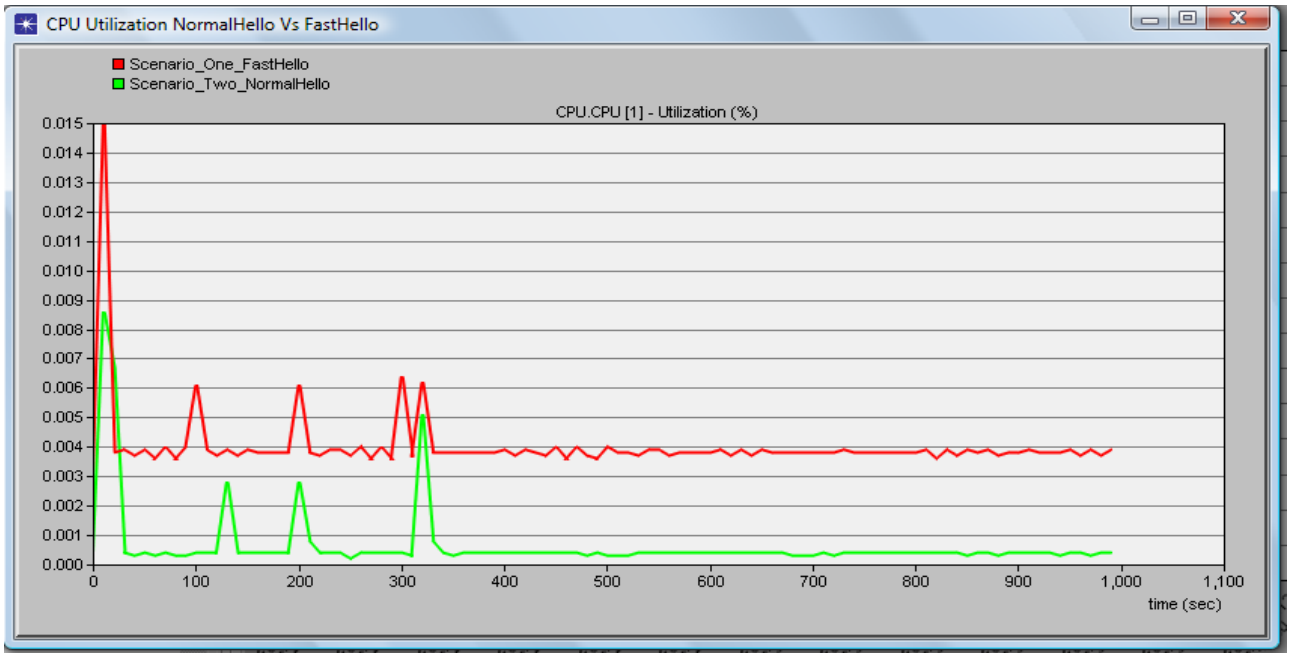


Figure 5.3: CPU utilization between fast and normal hello

	Initial Convergence	BACK_3 Failure (100 sec)	BACK_3 Recover (200 sec)	BACK_3 Failure (300 sec)	BACK_3 Recover (320 sec)
fastHello CPU	Y: 0.01500	0.00610	0.00610	0.00640	0.00620
normalHello CPU	Y: 0.00860	0.00280	0.00280	0.00510	

Table 5.2: CPU Utilization between *fastHello* and *normalHello*

2.) In the second scenario the selected node BACKUP_3 is made to go up and down continuously in 20 seconds interval between the simulations times of 100 and 300 seconds. The SPF style was periodic with a value 1.The goal was to show how fast reaction to such failures affects the CPU in *fastHello* as compared to the relatively delayed reaction in *normalHello*. The simulation result in Figure 6.4 shows that the CPU utilization shoots-up in both scenarios corresponding to the number of convergence durations.

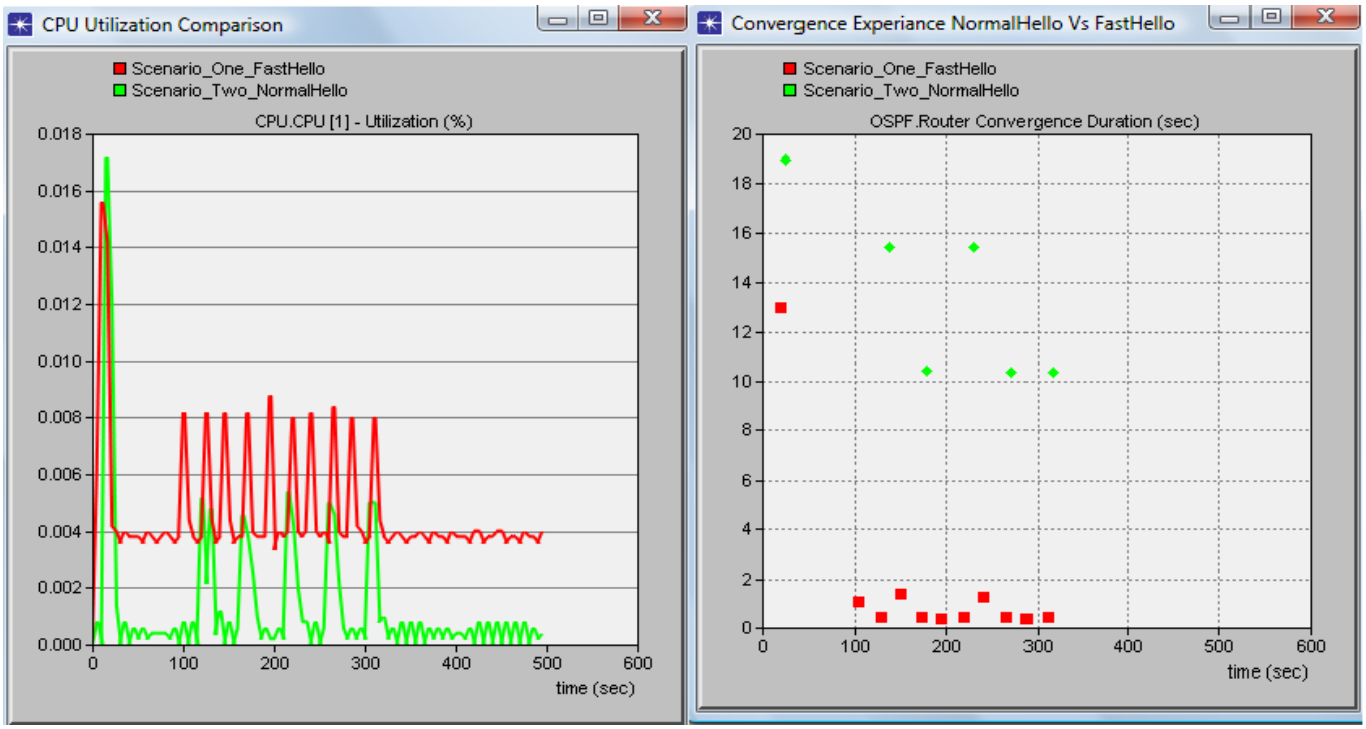


Figure 5.4: *fastHello* vs. *normalHello* reaction to continuous flaps

3.) The third simulation in Figure 5.5 shows the effect of concurrent node failures and recoveries on the CPU for *fastHello*. The effect was analyzed in three different scenarios. We used the twelve nodes in the left side of the simulated topology in Figure 5.1 to create three different scenarios. In the first scenario, the top four nodes were put down at a time at simulation time 100s and recovered at 200s. In the second scenario, a total of 8 nodes failed at simulation time 100s and recovered at time 200s. In the third scenario, all the 12 nodes were made to fail at time 100s and recovered at 200s. The SPF style used was periodic one second to create the maximum possible pressure on the CPU.

The 12 nodes, when seen in 3 pairs of each 4 nodes, have the same number of adjacencies to the back bone nodes; BACK_1 for example. This creates an interesting scenario to observe the CPU utilization trend on BACK_1 when different combinations of these pairs fail/recover at different times.

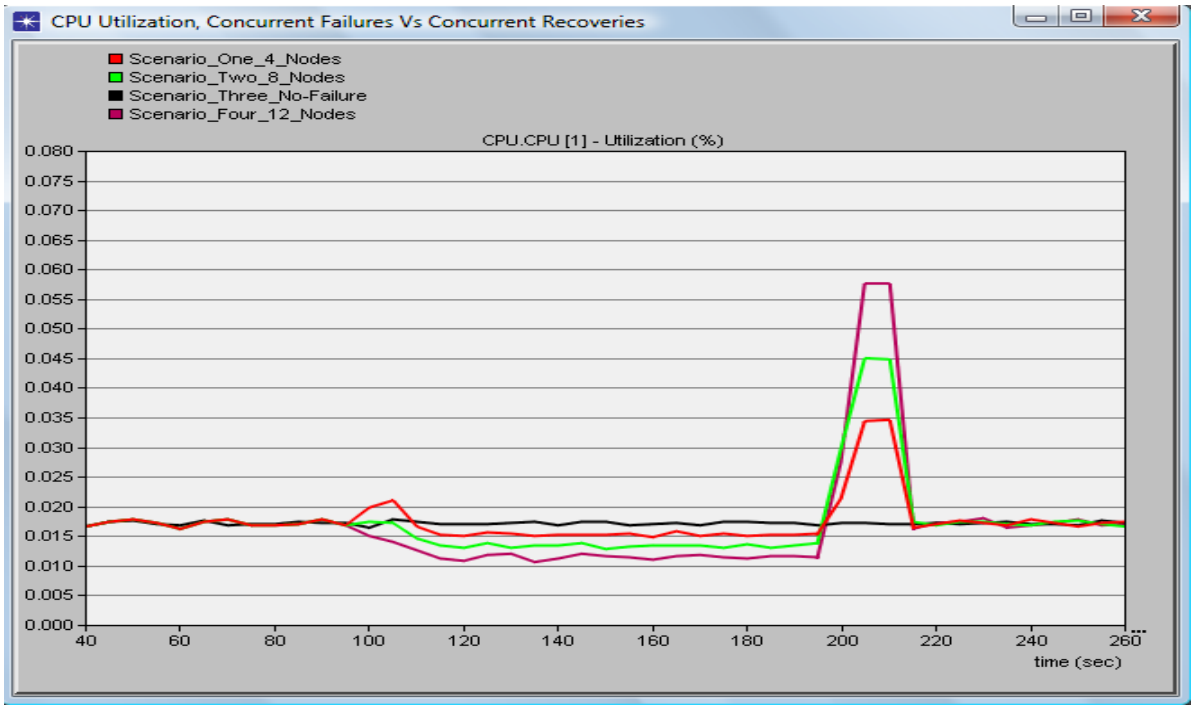


Figure 5.5: CPU utilization for *fastHello* under concurrent failures

From this result, we were able to conclude the following.

- The CPU utilization is highly dependent on the number of adjacencies that a router has. As can be seen from the above figure, The CPU utilization is inversely proportional with the number of failing nodes whereas it's directly proportional with the number of recovering nodes. This is of course is due to the fact that the more the number of the adjacencies ,the more will be the corresponding number of LSAs that a router needs to process, and OSPF operations including the SPF computation are highly dependent on the size of the link state database that contains all these LSAs .
- The Other interesting analysis is that even though the CPU consumption trend is generally decreasing for the failure case and increasing for the recovery, the relative changes are not the same i.e. it shows a sharp rise for the recovery and relatively a small change for the failure. Well, it's of course always easier to destroy than to create; a lot of OSPF messages have to be exchanged and processed since the neighbor relationships need to be re-created from scratch.

4.) The fourth part in Figure 5.6 shows how the network stability can be affected due to frequent node failure/recovery when using different values for the SPF hold value. This can be shown in OPNET Modeler using the next hop update parameter that shows the number of times the next hop of a given route is updated. The selected node BACK_3 is made to flap 20 times in 10seconds interval between the simulation times 100 and 300 seconds. This time the LSA_driven SPF style is used with initial delay of 1s and a hold value of 5s for the first scenario and initial delay of 1s and a hold value of 15s for the second scenario.

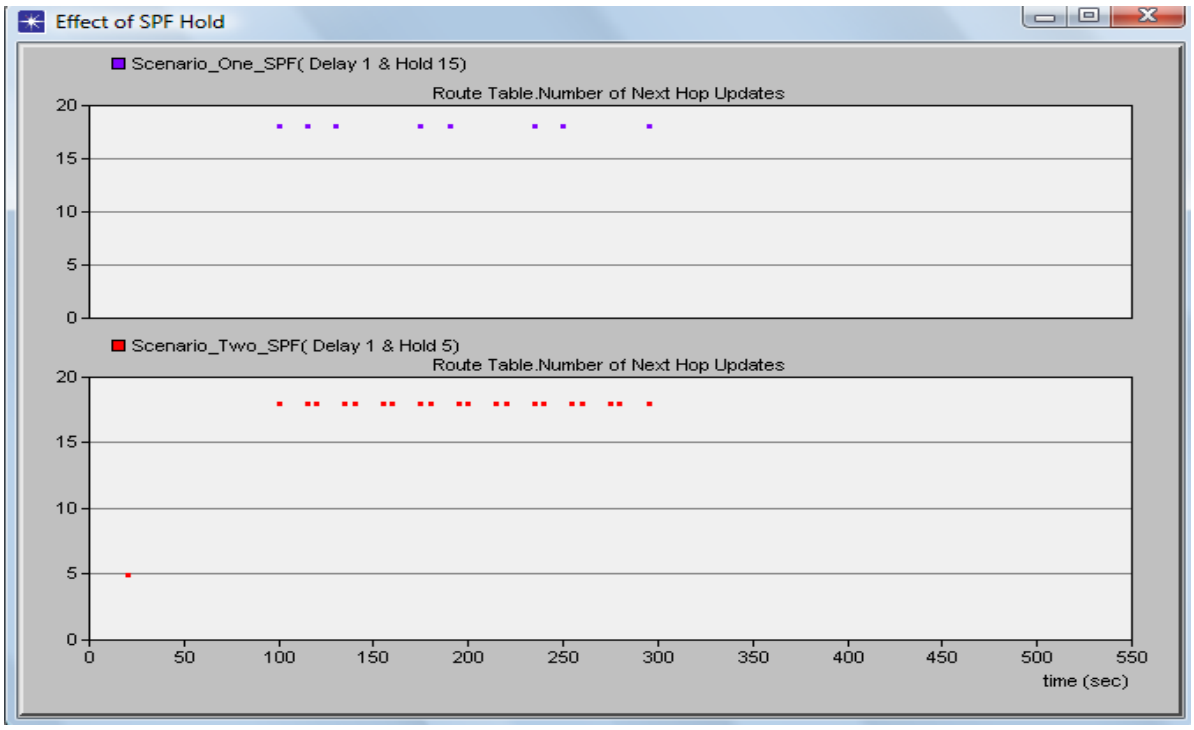


Figure 5.6: Number of next hopes updates in *fastHello* using SPF hold 5 and 15

As can be seen from the above figure the number of next hop updates for the SPF hold value of 15 seconds is 8 as compared to 20 for the SPF hold value of 5 seconds. A simple observation from this could be that the number of SPF calculations is delayed 2 times more for the former case; this gives more time to collect more LSAs before the SPF starts which results in fewer number of SPF calculation and route flaps.

5.1.5 **OMNETPP (**Objective Modular Network Test bed in C++)

OMNETPP is one of the promising and widely used simulation platform for modeling wireless/wired network communications and protocols. It also provides a strong GUI support though not as sophisticated as OPNET's solutions are. OMNETPP is not a simulator itself but it is a simulation platform that follows component based architecture with flexible and scalable simulation environment. All network models and protocols supported by OMNETPP such as OSPF are provided in a separate package called the INET framework. The INET framework is independent of OMNETPP but complies with its architecture. Simulated objects in OMNET++ are represented as modules which can be simple or compound. A simple module is a C++ implementation of a simple object such as a queue or a point to point interface whereas a compound module such as a network layer or a router is formed from two or more combinations of simple/compound modules. The following figure shows a compound module router and its building blocks.

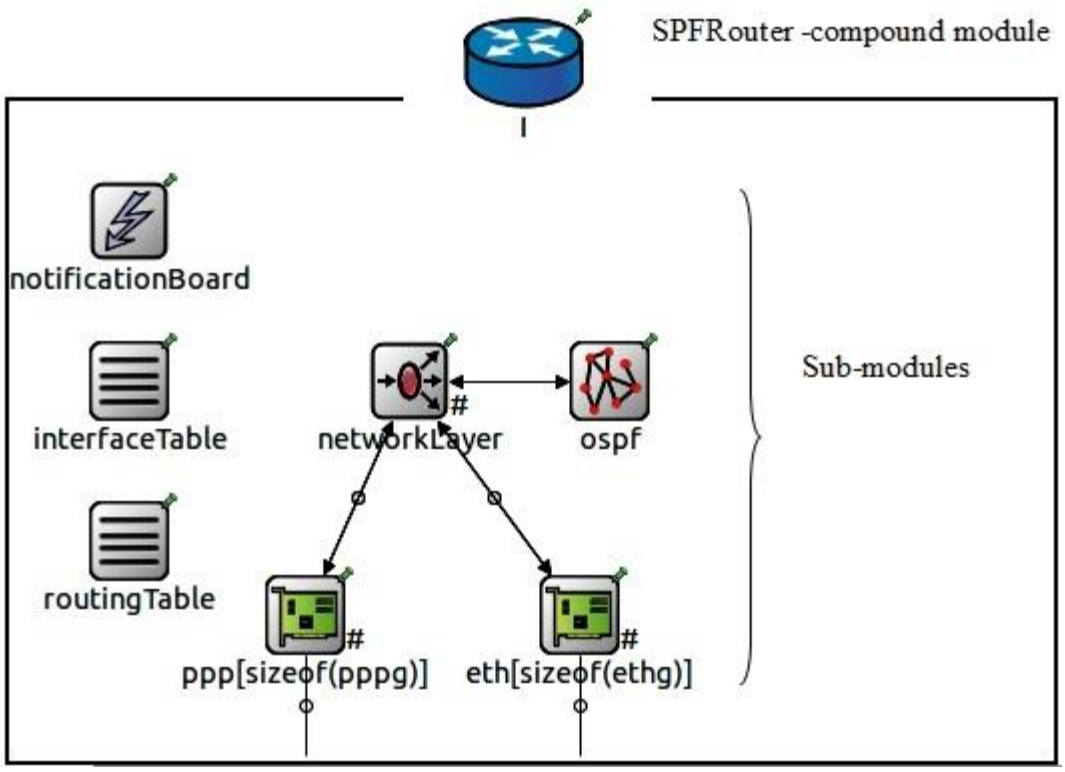


Figure 5.7: OMNETPP simple/compound modules

A network model in OMNETPP is created using a special Network Description Language called the NED language. All connections between simple/compound modules and other associated parameters are described using the NED language.

5.1.5.1 OMNETPP simulation components

A simulation model in OMNETPP consists of the following files:

NED files: Like OTcl is for NS-2 or python/C++ is for NS-3, topology information in OMNETPP is described using the NED language as mentioned above. The information contains the network name, a detail description of the sub modules forming the network and the description of the connection between them (channels, gates etc.).

Config. files: Contains OSPF configuration information; this includes information related to the areas (area id, area address range etc.) and routers such as router id and the description of its interfaces.

Routing information: this includes the router IP addressing details, metric, multicast/broadcast groups and static/default routing information.

Omnetpp.ini file: The Omnetpp.ini file describes what to run and with what parameters; it contains the names of the NED file, the configuration file, the routing files, and other run-time parameters. The following figure shows a screen dump of the above files in OMNET++ window.

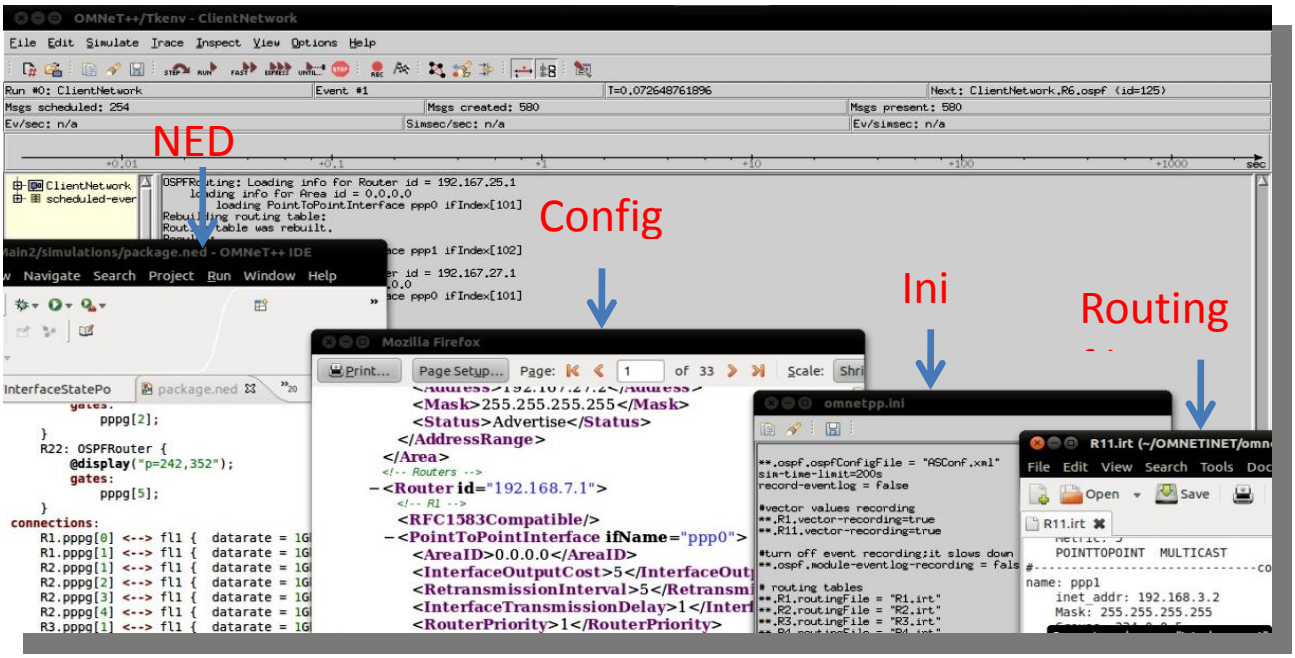


Figure 5.8: OMNETPP simulation components

5.1.5.2 OMNETPP OSPFv2 Issues

We chose OMNETPP for its free OSPF source code which of course has a few of limitations. Some of the issues were clearly stated by the developers and we have noted a few others during the source code review. Some of these issues along with their effect on our implementation are outlined below:

- The implementation has some unresolved issues related to unnumbered point to point links, as clearly commented by the authors. However, all connections between the routers in our network are numbered point to point.
- Unlike the other protocols such MPLS, OMNETPP doesn't have advanced simulation support for OSPF such as automated link/node failure and recovery. This would have helped to easily model a flapping interface. We have adopted a different way of achieving this which is discussed later on this chapter.
- OSPF operations such as checksum validation are not implemented. This is used to check whether the received OSPF messages are corrupted or not, but in our simulation we assumed all sent messages are received without an error since we didn't introduce a message loss or a bit-error factor in the simulation.
- The implementation doesn't make use of the *minLSAInterval* parameter; no gap between successive originations of the same LSA. The LSA throttling algorithm introduces a new dynamic implementation of it.

5.1.5.3 The simulated topology in OMNET++

The network topology we considered for the simulation is shown in Figure 5.9 It consists of 22 routers, with 47 links and 94 routes (each point to point link is added as separate route). The topology is made to not use equal cost multi-paths, to get a unique path through the network at all times. The green path shows the current shortest path from the source R1 to the destination R18 and the yellow line through R10 is an alternative redundant path that takes over when the link R10-R11 fails. R11 is selected as the target router that experiences the flapping interface; its ppp5 interface that connects it to R12 is brought Up and Down periodically to imitate a constantly oscillating interface. R1 is taken as a reference node to monitor the LSAs generated by R11.

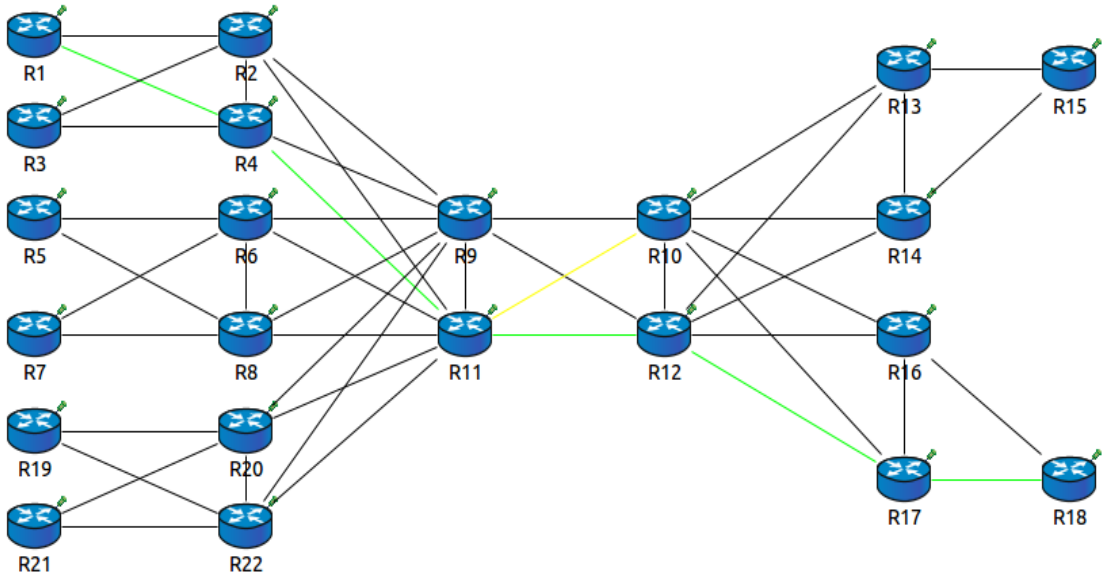


Figure 5.9: The simulated topology

5.1.5.4 Interface/Neighbor state changes following a link flap

Before we discuss the LSA throttling algorithm, it is important to review the LSA generation process corresponding to the Interface/Neighbor state changes in point to point links. As discussed in chapter 2, one of the possible ways a router could generate a new LSA is when its interface/Neighbor state changes. We will present an explanation of how this happens following the figure below. The figure shows how the interface state and neighbor states of an interface changes in point to point links as the selected interface is put down and up.

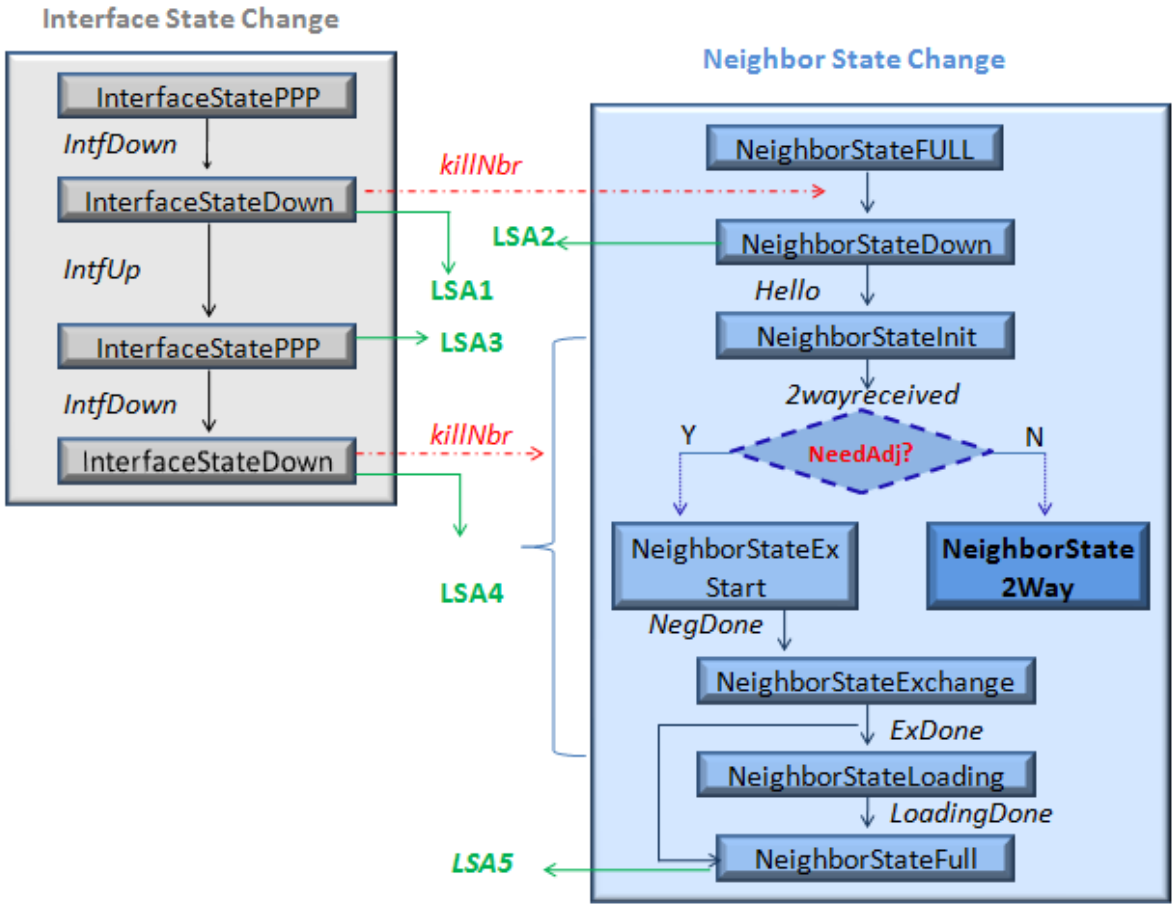


Figure 5.10: Interface/Neighbor state changes

Normally, when an interface is brought down, the following sequence of actions are taken by the router

- The interface's state is changed to DOWN .This may necessitate a new LSA generation (LSA1) that excludes the down link. The interface may not have a neighbor associated with it in this case.
- All the timers associated with the interface are cleared.
- A kill neighbor's signal(actually a function call to delete all the neighbor states associated with that interface) is sent to all neighbor objects associated with the interface following which all the neighbor data structures are cleared and also the inactivity timer(that fires every *routerDeadInterval* amount*)* is cancelled. Finally the neighbor's states are put to down. This is followed by a new LSA generation (LSA2) that excludes the down link states.

When the interface is brought up again, its state immediately changes to Point-to-point(note that this is not the case in broadcast links) and a new LSA (LSA3) is generated to advertise this, but the link is advertised as a stub link if the adjacency over it is not yet fully established. The neighbor state transitions all the way from *init* to *full* upon which the router once again generates an LSA declaring the availability of a fully functional route (LSA5). The neighbor state may jump from an exchange

state to full state as shown in the figure following an *exDone* event if the link state request list of the router is found empty(i .e all the LSAs are already exchanged). Note that if the second kill neighbor signal is sent to a neighbor state that is in any of the states less than the *full* State, no LSA will be generated as a result, rather the neighbor state is restarted from *init.*

The above sequences of actions were put ambiguously in OSPFv2 source code leading to unnecessary LSA generation. That was corrected following the discussions with our supervisor. However, with the LSA throttling feature enabled, we don't have such issues as the LSA generation is no longer event driven but rather controlled by the LSA throttling timers.

5.1.5.5 The convergence process in simulation

The simulation results of the CPU time taken for each of the convergence factors described in chapter 2 are shown in table 5.3 We will explain the approaches used below:

Failure detection time: This is the duration from the failure of a link/Node until the OSPF process is informed of the failure. In our case, the failure detection time is the duration from the time the given interface is brought down using the *interfaceDown* event triggered upon the expiry of the *interfaceDown* timer until the router performs all the necessary changes following the failure (see section 6.1.3.4) but before the corresponding LSA is originated.

Propagation time: this is the duration from the start of the LSA origination until it is received by the farthest router in the network (depends on the network diameter). This includes the time for the LSA origination, flooding, reception and processing time by a receiver which includes identifying the LSA for new/duplicate, re-flooding and acknowledgment among others. An initial LSA delay time is also added to this if any is configured.

SPF run time: this is the CPU time taken to compute SPT for the network. The SPT is computed for the given network of 94 routes. Note that each point to point interface assumes a separate route in the routing table and added to the routing table as a separate route unlike broadcast links where a single route is added for adjacent links that share a common sub network address.

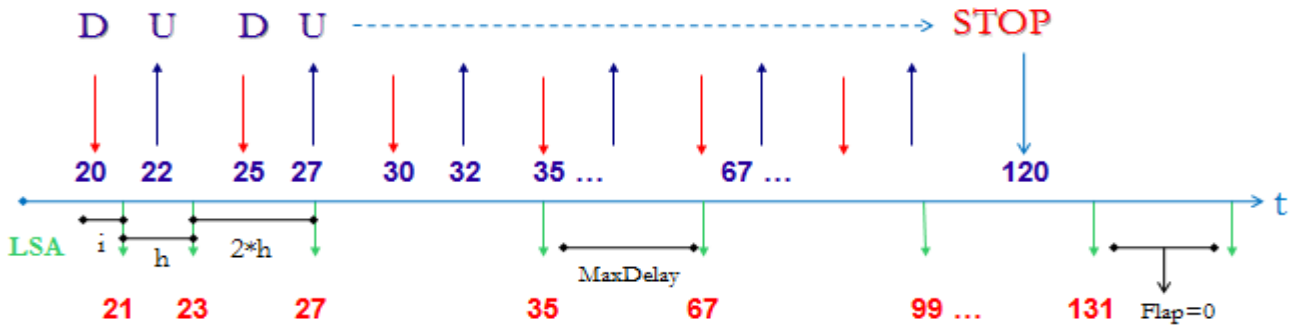
FIB Update time: OMNETPP simulation doesn't consider FIB update times; it assumes an ideal router with FIB update time 0. So, routes are already added to the routing table when the SPF computation returns. As a result, this time is considered zero in our case. Note that in real world scenarios, the FIB update time takes the maximum share next to the event propagation time in the convergence process. The table below shows the average CPU times for the above operations.

Operation	Average CPU-time(*ms*)	Remark
Failure Detection	0.050	Time from a failure of PPP6 interface of R11 until LSA generation starts; this actually doesn't correspond to the real detection time as we manually down the interface in the code itself.
Event propagation	145.96	Time from LSA generation by R11 (target Node) until SPF starts at R1 (reference Node).LSA/SPF initial delay is assumed 0.
SPF computation	2.65	SPF computation and routing table update
FIB update	NA	Not applicable
Total Convergence Time	148.66	Total Convergence time for a down event

Table 5.3: Total convergence time

5.1.5.6 LSA Throttling

The LSA throttling algorithm works under the presence of a link flap. In the real case, the flap is notified to the OSPF process by the available failure detection mechanism. Figure 5.11 shows the periodic UP (U) and Down (D) Timers and the LSA throttling timers in action as the ppp5 interface of R11 flaps.



Timers	IntfDownTimer(D)	IntfUPTimer(U)	LSAInitialDelay(*i*)	Hold(*h*)	MaxDelay
Intervals(s)	2	3	1	2	32

Figure 5.11: LSA throttling timers

As can be seen from the figure, the interface down event (D) starts from time 20; the delay is to give enough time for the initial convergence which is the total time that each router takes to acquire all the routes in the network initially. The LSAInitialDelay*(i)* is assumed to be 1s; this is an important parameter to be tuned carefully in real network deployments because it has a significant impact on the convergence time. The general rule of thumb is to keep it as small as possible (5-10ms, Cisco) but large enough to incorporate multiple changes that might occur synchronously (e.g. simultaneous link failures when a routers fails). The hold value starts from 2s and it grows exponentially until *MaxDelay* after which it keeps this value so long as the flap. It will be reset back to its initial value if no sign of flap is detected for a duration of 2**MaxDelay*. The Up and Down timers are rough estimations fulfilling the following conditions:

- The UP time (3s) is chosen in such a way that there would be enough time for Router11 to establish a full neighbor relationship with its adjacent router R12 before it is brought down.
- The Down time (2s) should give enough room for the adjacency to be fully torn down before it is brought up again.
- The inactivity timer is assumed not to fire following a down neighbor, for the down interval of 2 seconds is less than the *routerDeadInterval* which is 4 second and at least one hello must be received before it expires. This is automatically taken care of by the OSPF process when the neighbor state is brought down. But even if this timer fires leading to LSA generation, the LSA generation is subjected to follow the LSA Throttling delay.

Below are shown the pseudo code for some parts of the implementations related to the timers.

Notations:
router is a pointer to a Router
intf is a pointer to an Interface
nbr is a pointer to a Neighbor
msgHandler is a pointer to MessageHandler

```
Upon expiry(timer  intfDownTimer)
        If router=TARGETROUTER then          // get the target router with a flaping interface
                Intf <--getInterfacebyId(intfId)                  // get a reference to an active interface
                Set intf.state<--DOWN                             // fail the interface
                Timer intfUPTimer<--router.getIntfUpTimer()       // get a reference to the Up timer
                start(timer intfUPTimer,double upInterval)        // (re)schedule the UP timer

Upon expiry(timer  intfUpTimer)
        intf<--intfUpTimer.getContextPointer()            // get a reference to the interface from
        Set intf.state<--UP                               // the timer context and recover it
        start(timer intfDownTimer,double downInterval)    // reschedule the Down Timer

Upon expiry(timer  stopTimer)    // stop the flap timers and make sure the intf is Up finally
        If isRunning(timer intfDownTimer) then
                stopHandler.clearTimer(intfDownTimer)
        else if isRunning(timer intfUPTimer) then
                stopHandler.clearTimer(intfUpTimer)
        If intf.getCurrentState()=DOWN then          // make sure the interface is up finally
                Set intf.CurrentState=UP
```

```
Upon expiry(timer lsaDelayTimer)
        Intf<--lsaDelayTimer.getContextPointer()        // get a reference to the interface from the timer context

        // track the presence of a flap using the flap counters associated with each interface or using the neighbor
        // inactivity/linkDown counter associated with the neighbors on each PPP interface
        // a sequence No. mismatch error may also occur leading to LSA generation  when a router suddenly resets
        // its sequence number due to interface Down event before the other peer detects the failure.
        If  intf.getFlapCounter()>=1  or
           intf.getNeighbor.getInactivityCounter>=0 or
           intf.getNeighbor.getLinkDownCounter>=0  or
            intf.getNeighbor.seqNoMistmatchCounter>0  then
                router.OriginateRouterLSA()                                  // generate the LSA
                If 2*intf.GetLSADelayInterval()>=MAXDELAY then    // delay shouldn't  exceed MAXDELAY
                    intf.setLSADelayInterval(MAXDELAY)
                Else
                    intf.setLSADelayInterval(2*GetLSADelayInterval())      //double delay until MAXDELAY
                msgHandler.startTimer(intf.lsaDelayTimer, intf.GetLSADelayInterval())  // re schedule delay timer
                // reset all the counters associated with a link/interface flap
                reset(flapCounter)
                reset(inactivityCounter)
                reset(linkDownCounter)
                reset(seqNoMMCounter)
        Else
                intf.resetLSADelayInterval()            // reset the delay interval to its initial if the flap stops
                DelayHandler.clearTimer(router.lsaDelayTimer)          // cancel the timer
```

Table 5.4: Pseudo codes for LSA Throttling timers

The following two figures show Router 11's LSAs as they arrive at R1. Figure 5.12 shows LSA arrivals without the LSA throttling feature and figure 5.13 shows the arrivals with LSA Throttling enabled. The red spot at around simulation time 10 shows the initial convergence time; i.e. the last route insertion time where R1 has installed all the 94 routes. This time is almost the same for all routers with only a slight variation of a few milliseconds. The average value is 10.092 simulation seconds.

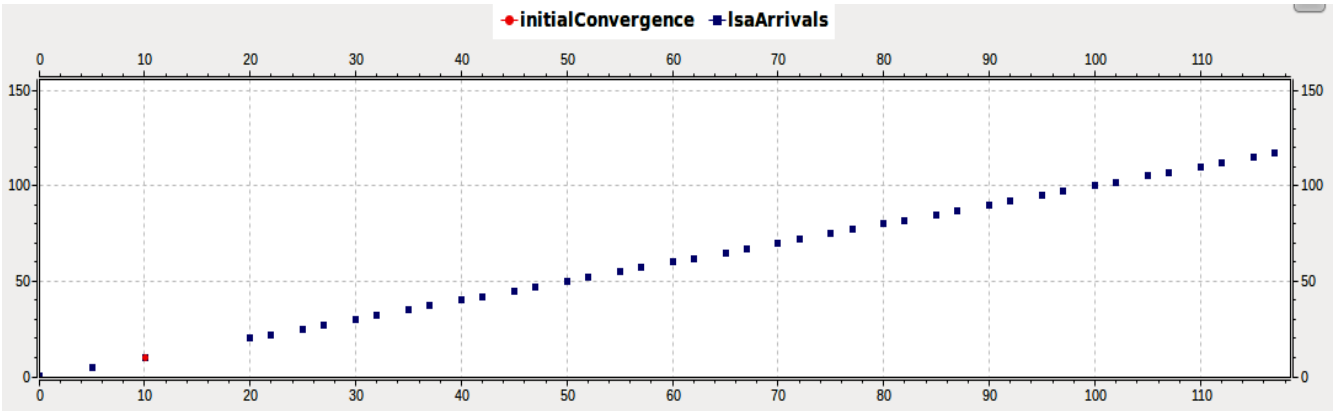


Figure 5.12: Original LSAs as they arrive on R1

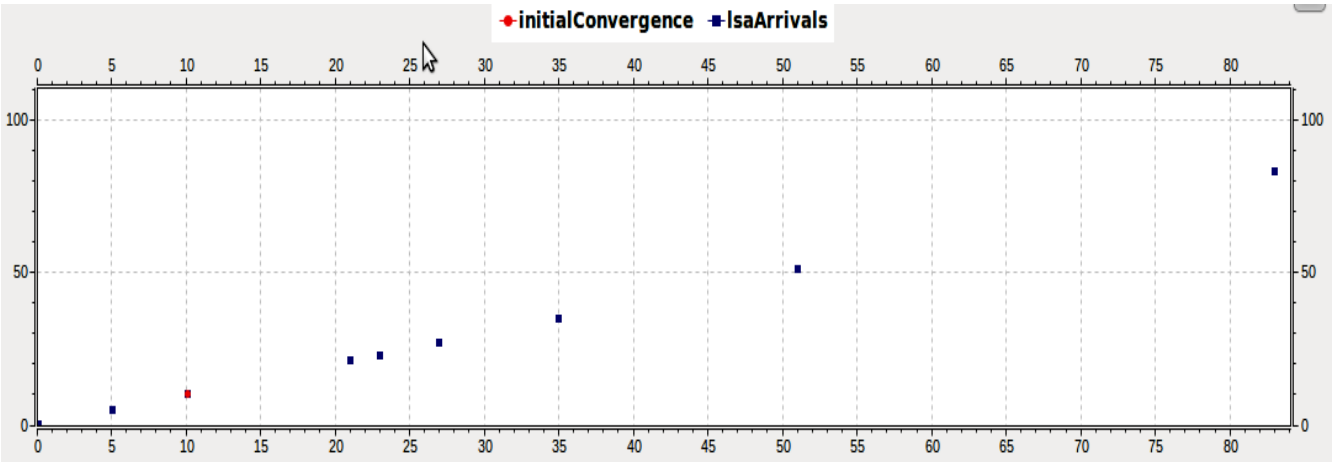


Figure 5.13: Throttled LSAs as they arrive on R1

As can be inferred from the graphs, without the LSA Throttling functionality, a persistent link flap would generate at least one LSA for each Up and Down event and all the generated LSAs are received by R1. With the LSA throttling functionality enabled on R11, the number of LSAs R11 generates are exponentially delayed and as a result a fewer number LSAs are received by R1. The number of LSAs drops from 43 to 9 which is a significant change. It's not just the decrease in number that is interesting but it's important to see what each LSA could have cost the network if they were not throttled. It requires the total convergence time for the network to stabilize for a single LSA, and if such LSAs are originated in close succession, all the routers have to repeat the same process over and over adding and deleting the same route. The network would be in continuous disturbance and never stabilizes. This might have very disastrous consequences that could lead to a network wide dysfunction especially if such events occur in large scale.

5.2 Considerations for broadcast networks

Fast convergence in all types of OSPF networks are affected by the value of the timers set. However, different network types exhibit different convergence property due to their inherent design differences and OSPF's mode of operation. For example, it can be generally said that point to point networks convergence faster than broadcast networks for so many reasons one of which is due to the fast failure detection provided by the layer 2 protocol. The OSPF's mode of operation in point to point networks is the simplest type. One of the reasons is that there is no notion of DR/BDR and an adjacency is formed between all neighbors straightaway unlike the broadcast/NBMA networks that take up some time for DR/BDR election/re-election.

The other delay factor in broadcast/NBMA networks is that interface state changes in broadcast networks involve a waiting time (equivalent to the *routerDeadInterval*), a time that an interface has to wait before it transitions to either DR, Backup or DRother state, this significantly affects the initial convergence as well as every other re-convergence following each time a link is UP or a router restarts.

While the presence of DR/BDR in broadcast networks reduces the number of adjacencies, it exposes the network to a single point of failure and also it requires the DR/BDR to originate a new type 2 LSAs to communicate changes to all the nodes in the network. This increases the overhead in the network. If both the DR and BDR happen to fail at a time, the network performance will be highly degraded. Multiple adjacencies are dropped simultaneously and a new DR/BDR re-election needs to be undergone. All topology changes in the meantime will not be communicated leading to a delayed convergence.

The LSA generation delay algorithm applies to all types of OSPF networks in the presence of a link flap, but the effect varies a little. This is due to the difference in the traditional failure detection mechanisms used in those network types. Unlike the point to point networks that have link layer failure detection mechanism, broadcast networks can't detect failures that occur behind the switch so quickly but after the *routerDeadInterval*. This means that they are unresponsive to frequent link flaps that may happen within the *routerDeadInterval* in contrast to the former that are aware of such events as they occur and react instantly. The use of a BFD session over a layer 2 switch is an alternative fast failure detection mechanism for broadcast links.

6. Conclusion and Future work

OSPF is one of the prominent and widely studied IGP routing protocols in ISPs and enterprise networks. Since the latest RFC2328 released more than a decade ago, there have been numerous changes in both its traditional configuration of parameter such as timer values as well as changes due to optimized ways of working in many of its operations. Most of the important operations of OSPF that contribute to its fast convergence such as failure detection, SPF calculation, LSA generation and flooding are controlled by timers. Some of these timers have traditionally been considered as architectural constants whereas as the rest were a one-time set fixed values. Modern experiences and research works suggest a dynamic implementation of these timers for a safer network operation and faster convergence to failures. Dynamic timers are generally set to a small initial value based on the expected network stability level and the values vary with the experienced network load. This adds robustness for the OSPF operation at times of instabilities as well as improves the network convergence speed at times of stable network operations.

This work in part revises what has been achieved in OSPF fast convergence so far, with a more focus on the use of dynamic timers. Stability issues that come with reducing the timer values have also been discussed supported by simulation results for some selected scenarios. The simulation results show that while fast hellos of one second are good choices for fast neighbor discovery and failure detection, they may not be that effective for continuous but brief link/router breakdowns that are common on real network deployments. We have also concluded that the CPU consumption highly depends on the number of adjacencies a router has. This work has also introduced the pseudo code as well as the implementation and evaluation of the LSA throttling algorithm. The simulation results demonstrate that an OSPF network using this feature has a much lower number of LSAs generated at times of persistent link/node flaps. Having this dynamic technique is crucial to achieve fast convergence taking the CPU and network stability into consideration.

Fast convergence to network changes is one of the desirable properties of OSPF and other routing protocols. Experiences indicate a combination of different techniques are used in each operational phases of OSPF to achieve sub-second convergence. Simulation results modeling real ISP networks of hundreds of nodes show that the hello timers can safely be reduced to a few hundreds of milliseconds for fast failure detection. Although the use of fast IGP keep alive timers seems to be inefficient in terms of the heavy processing load, a dynamic implementation of this, along with a routing protocol independent BFD technique is still highly recommended for fast failure detection on broadcast networks. BFD with IP-event dampening technique is a recommended combination for fast failure detection as well as suppression of false alarms. LSA throttling is used to provide dynamically controlled LSA generation against link flaps. SPF Throttling is best used with LSA throttling to provide dynamically controlled SPF computations for self-generated or flooded LSAs. While using these throttling techniques, it is very important to tune the initial delays carefully as it highly impacts the convergence duration for occasional and transient network failures.

New variants of SPF algorithm such as iSPF with a dynamic scheduling scheme are best to minimize the CPU overhead on large networks. Dynamically tuned packet pacing delay timers are also recommended for optimized flooding and retransmission. Incremental FIB update techniques provide optimized performance by only updating modified IP route prefixes instead of a full dump.

Recent proposals on minimizing packet drops during the convergence period suggest a mechanism to avoid communication breakdown at times of link/node failures through the use of alternate locally determined paths without requiring explicit notification of the failures globally. Details can be found on as RFC 5714, 2010.

Future works on OSPF fast convergence and stability issues may consider the implementation of the LSA throttling algorithm or other similar dynamic timer techniques on broadcast networks. We also would like to recommend the use of emulators instead of simulators for a close-to-real network analysis of results as the emulated network can be extended to a real network node.

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Appendix 1

1. OSPF Basics

1.1 OSPF Protocol Overview

The Internet Engineering Task Force (IETF) started working on a routing protocol named OSPF in 1987 to replace a famous, by the time, distance vector routing protocol named RIP (Routing information protocol). RIP consumes higher bandwidth during its update and its convergence time did not go well with the growth of the IP (Internet Protocol) network by that time. The development of the OSPF protocol is basically prompted by the failure of RIP to address the problem related with the growth of the IP network at the time. The development of the OSPF protocol started with the aim of achieving faster convergence time taking less bandwidth consumption during updates.

OSPF is a dynamic link state routing protocol that interconnects routers exchanging information within a network. The protocol's dynamicity comes from the fact that it maintains its routing table with possible routes and updates it periodically. It performs a real-time calculation up on changes in a network. It is a link state routing protocol since each router in the network tracks the link status of a network. It is an Interior Gateway Protocol (IGP) since it operates within a single AS (Autonomous System), and it is one of the most widely used IGP in large enterprise networks. It operates on the TCP/IP protocol suite encapsulated within the protocol number 89. It uses IP multicast to exchange routing information among routers in a network.

Routers configured with OSPF in a network are able to learn routes to other routers in the network dynamically, and they will pass the learned information among each other. The main goal of sharing link state information between routers in an OSPF network is to construct and maintain the same link state database (LSDB) about the whole topology of a network on every router. It is a requirement in an OSPF network. LSDB has a collection of routes and their active interfaces, as well as the cost associated to use each active links on a router. Making itself as a root node each router is expected to construct the shortest path tree (SPT) to every available node in a network. The SPT is constructed using the dijkstra's algorithm. The dijkstra's algorithm makes use of the lowest link cost as the best metric. The cost associated with every link is to give a priority among different routes in a network. Finally, each router constructs its routing table from the tree.

After constructing its routing table an OSPF router maintains a synchronized routing table with its neighbors. In an OSPF network the *hello* protocol is used to discover neighbors, and maintain connectivity between neighbors. The *HelloInterval* timer must be the same within a single network and it is used in conjunction with the *HelloDeadInterval* timer. The default time interval for *hello* packet is 10 seconds for an Ethernet link and 30 seconds for a non broadcast link [1][2]. If *hello* packets are not received by a router within the *HelloDeadInterval* time, which is usually four times than the *HelloInterval*, the router declares that its neighbor is down. This change is reflected by flooding a Link State Update throughout the network. The Link State Update packet only carries the changed link state information instead of carrying the whole LSDB. The flooding enables all the routers to synchronize themselves to the change.

1.2 OSPF Autonomous System(AS) and Areas

1.2.1 Introducing the concept of AS and Area

A group of interconnected routers that make use of a common routing protocol or a collection of routers under the control of a single administrative policy is termed as an AS. In Figure 1 below there are two separate AS's domain.com and reskit.com. Communications among the different networks with in some large AS is done using IGP, and Boarder Gateway Protocol (BGP) is used for the purpose of communication between one AS and another AS. As the size of an AS gets larger, the amount of link state advertisement exchanged and the size of LSDB that should be kept at each router in the AS also grows. Therefore, as the size of the AS gets larger each router is required to have a high processing capabilities and a large memory size to store the LSDB. Large ASs ends up in having large size of routing table which contains all the reachable information.

A router in an AS maintains identical LSDB, which results after a high routing information exchanges in the network. An OSPF network allows a large AS to be broken down to a group of networks called *area*s. An a*rea* is a collection of contiguous networks, routers and links that has the same *area* identification, say *Area* 1. Breaking down the AS in to different *area*s minimizes the size of the LSDB on each router to be stored and reduce the processing overhead of the SPT tree in constructing the routing table. Each *area* has its own LSDB and runs its own separate link state routing algorithm. Having a*rea*s in an AS enables to organize the network in hierarchical structure, and this capability gives the OSPF a true scalability and strength. Several *area*s can be found within an AS; only routers with in an *area* are expected to have the LSDB, i.e. routers have the knowledge of the *area* they belong to instead of the entire AS. Topology of an *area* is only known to the member routers, routers that belong to say *area* B cannot see the topology of an a*rea* A that belongs within the same AS. Isolation of topological information from *area*s reduces the routing traffic that is needed to be exchanged.

Depending on the destination address of a router, there are two types of routing with in an AS, intra-*area* and inter-*area* routing. Intra-*area* routing uses exclusively the available information with in the *area*; it won't use any routing information obtained from other *area*s and this will protect it from injected bad routing information.

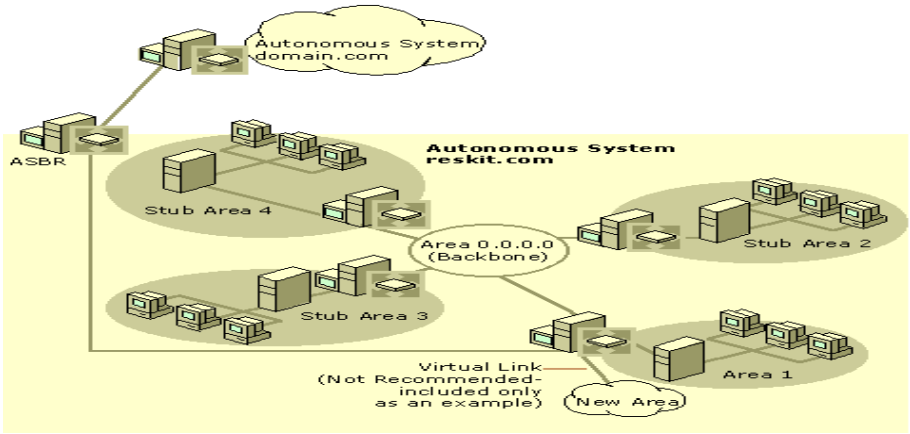

Figure 1.1: AS and Stub *areas*

1.2.2 OSPF Area Types

1.2.2.1 Backbone Areas

The backbone *area* is the first and special *area* that should be built when an OSPF network is configured. It is denoted by a*rea* 0 and can be described as 0.0.0.0[1]. Once a backbone *area* is configured other *area*s connect to it. Inter-*area* communication is done using the backbone as a hub .The backbone *area* includes routers that are located on boarder of *area*s called *Area* Boarder Routers (ABRs). Routers that are found in the backbone need to be adjacent but if they are not physically adjacent then virtual links can be configured for their connection [1]. A traffic flow between two non-backbone *area*s *area* 1 and *area* 3 in the Figure1 above, is done in a way that the traffic first flows from *area* 1 to the backbone *area* then the traffic flows through the backbone *area* 0.0.0.0, and finally the traffic is directed to the final destination *area* 3.

1.2.2.2 Stub Area

Stub *area*s in OSPF network are *area*s with a single exit point, designed usually for routers with limited resource capabilities like memory [3]. The stub *area* is only connected to the backbone *area* and it works in a way that no outside traffic from the AS can be flooded to it. This allows routers in the stub *area* to maintain a small link state database. Stub *area*s however accept route information about other *area*s within the same domain (inter-*area* routing information). An ABR that is configured for a stub network injects a default route, instead of advertising external routes, into the stub *area* so that the routers inside the stub can use it to reach out to external networks. Stub *area*s can be configured for a sub or branch offices that may not require knowing route to other sub branch offices instead it will use the default route to reach the main office and from there it can find all route information.

1.2.2.3 Totally Stubby Areas

As stub *area*, a totally stubby *area* is only connected to the backbone *area* and does not allow external routes to be flooded to it. It only allows intra-*area* and the default routes to be propagated within the *area*, which means routers only keep routing information about the totally stubby *area* and the default route in their LSDB. All inside routers use the default route injected by the ABR ,configured at the stubby *area*, in order to route any traffic between the totally stubby *area* and other a*rea*s within the same AS or external to the AS.

1.2.2.4 Not So Stubby Areas (NSSA)

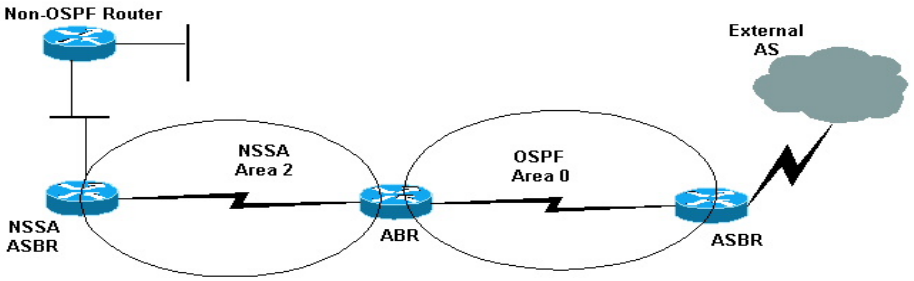

Figure 1.2: NSSA

It operates as a stub with the modification that it can import AS external routes and send it to the rest of the OPSF network. It works in a flexible way that it can inject external routes in a limited fashion to the NSSA *area*. Since the NSSA *area* is learning external routes through Autonomous System Boundary Router (ASBR), a new type of LSA (Link State Advertisement) called Type 7 LSA come in to the place. The Type 7 LSA is created by the ASBR and forwarded to the backbone using NSSA's ABR. The NSSA's ABR converts the Type 7 LSA to Type 5 LSA when it forwards the external routes to the backbone. NSSA is supported in Cisco IOS 11.2 and the later versions.

1.2.2.5 Totally NSSA

Totally NSSA is an extension to the NSSA; it is a type that is preferred when only one exit point exists. In totally NSSA Summary LSAs and external LSAs are not allowed. The default route is injected as a summary route and Type 7 LSAs are converted into Type 5 LSAs at the NSSA ABR.

Totally stubby *area* and NSSA totally stubby *area* are proprietary extensions implemented by vendors like Cisco, Juniper, Alcatel-Lucent, Huawei, Quagga, though not specified in the RFC 2328 and they are considered now by many as standard features.

Below is presented a summary of the different types of OSPF Areas. The different types of LSAs in an OSPF network have been discussed in section 1.6.

Types of *Area*s	Restrictions
Normal	None
Stub	No Type 5 AS-external LSA is allowed
Totally Stubby	No Type 3, 4 or 5 LSAs are allowed except the default summary route
NSSA	No Type 5 AS-external LSA is allowed as it is a stub. Type 7 LSAs can pass through the NSSA and it is converted to Type 5 at the NSSA ABR.
NSSA Totally Stub	No Type 3, 4 or 5 LSAs but the default summary route. Type 7 LSAs are converted to Type 5 at the NSSA ABR.

Table 1.1: Summary of OSPF area types

1.3 OSPF Network Types

The OSPF protocol supports in general the following types of networks [1]:-

- Point-to-Point networks
- Broadcast networks
- NBMA(Non-Broadcast Multi-access) networks
- Point-to-Multipoint networks

- Virtual links

1.3.1 Point-to-Point networks

Figure 1.3: Point-to-Point network

A Point-to-Point network is the simplest type of network that connects two routers directly with each other. Any packet sent from one side will have only a single recipient on the other side and it is considered as a single network [1]. Point-to-Point networks use the multicast address that works for all routers running OSPF (224.0.0.5) to exchange any OSPF packets.

1.3.2 Broadcast Networks

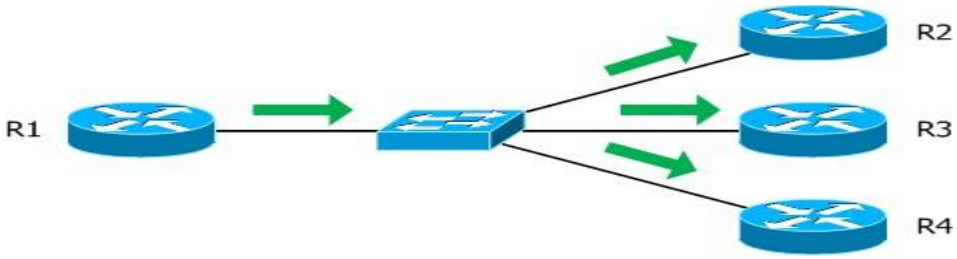

Figure 1.4: Broadcast Network

A broadcast network is a type of network that supports more than two attached nodes. It has a capability of sending a single message to all routers in a network and such network is important when setting large number of communicating devices [1]. Ethernet, Token Ring, and FDDI, can be taken as an example of broadcast multi-access networks. It makes use of a multi-access segment like switch for efficient way of communication, since switch has the tendency to multiply a single incoming packet to reach out to all connected nodes. The switch's capability helps in saving bandwidth in the network [1]. Using such types of network simplify the neighbor discovery process. Neighbors are discovered dynamically using the *hello* protocol packet that takes advantage of the nature of the network, no need of prior knowledge about neighbors presence.

OSPF routers in a broadcast networks can end up forming several neighbor relationships with each other due to the presence of multi access segment. The desired feature is to have as simple adjacencies as possible. As a result, nodes on multi-access segment elect special nodes from the available nodes in the network called designated router (DR) and backup designated router (BDR). Both DR and BDR are termed as AllDRouters. Having a DR and BDR helps to achieve better management of the LSAS in a network. All routers other than the AllDRouters are called DRothers.

The election of DR and BDR is done with the help of the *hello* protocol, and the election process makes use of the routers priority or the router ID advertised in the *hello* packets exchanged. All nodes in the network including the BDR will form adjacencies with the DR. The nodes are also expected to form adjacency with the BDR, to be used as a backup in case of DR failures [1]. Here a network of four routers can have 12 adjacencies to form mesh network if the DR and BDR are not in place but, with the existence of the DR and BDR only 5 adjacencies information is required [1]. As mentioned in section 2.4.7, the DR is also responsible in generating the Network LSA.

In broadcast networks OSPF routers use the following two reserved IP multicast addresses 224.0.0.5 and 224.0.0.6. All routers use the IP multicasts address 224.0.0.5 to send the h*ello* packets to AllSPFRouters, routers running OSPF. This multicast IP address can also be used by the DR to flood updates to the DRothers. The multicast IP address 224.0.0.6 is used by the DRothers to send updates to the AllDRouters, this address can only be listened by the DR and BDR. Being a DR is a property of routers interface not the whole router. Therefore, a router can be a DR on one of its multi-access network and it may not be on its other interface.

1.3.3 Non-broadcast Networks

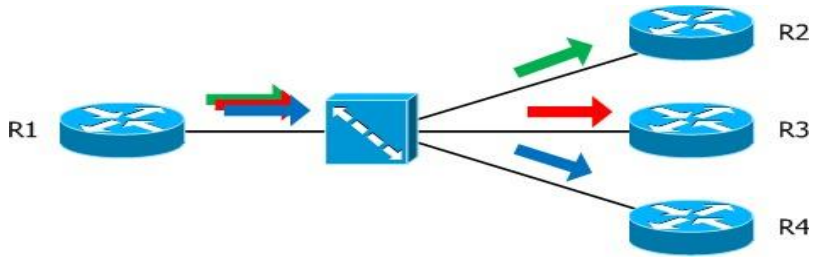

Figure 1.5: Non-Broadcast Network (Frame Relay Topology)

Non-broadcast networks support more than two routers in their network but have no broadcast capabilities [1]. This explains that all multi-access technologies do not support broadcast capabilities. Some of the examples of the non-Broadcast networks are X.25 Public Data Network (PDN), frame relay and ATM that needs a configuration of individual permanent virtual circuits (PVCs) between their end points [1]. Neighbor relationships are maintained using the *hello* protocol that are sent individually instead of being multi-casted, since the network lacks the broadcast capabilities. But in such networks neighbor discoveries may require some prior configurations. NBMA and Point-to-Multipoint are the two main modes of operations in an OSPF non-broadcast network [1].

1.3.3.1 Non-Broadcast Multi-Access(NBMA)

The NBMA simulate Broadcast network in order to address its broadcast incapability. OSPF *hello* packets or link state packets are individually sent from a node as a unicast packet to adjacent neighbors. Each router in NBMA is configured with the IP address of its neighbor as a destination IP address. DR and BDR are also elected to reduce the adjacencies that need to be formed.

1.3.3.2 Point-to-Multipoint

As its name describes the Point-to-Multipoint treat the non-broadcast network as a collection of Point-to-Point links and does not try to emulate the broadcast capability. As in NBMA individual *hello* packets replication is needed but in this approach there is no need for DR or BDR that is no Type-2 LSA.

1.3.4 Virtual links

A Virtual link is a link that is used to connect to the backbone through a non-backbone *area*. In such links OSPF packets are sent as unicast.

1.4 OSPF Router Types

1.4.1 Backbone routers

Back bone routers are routers that belong to the backbone *area* (*area* 0). These routers can have one or more interfaces in the backbone *area*. The *area* 0 is expected to have at least one backbone router in its *area* [1].

1.4.2 Internal routers

Internal routers are those that have all their interfaces inside one *area* only, they are connected only to one *area* [1].

1.4.3 Area Border Routers(ABRs)

ABRs are routers that are connected to more than one *area*. They are usually placed at the boarder of an *area* to connect a non-backbone *area* to the backbone one, having its interfaces to both a*rea*s. ABRs have multiple LSDBs, one for each attached *area*.

1.4.4 Autonomous System Border Routers(ASBRs)

ASBRs are routers that connect one AS to another AS that runs under different protocol. ASBRs are routers that are used to distribute external routes from outside the AS.

1.5 OSPF Packet Types

Packet name	Type	Description
Hello	1	To discover and maintain neighbors
Database description	2	Summarize database contents
LinkState Request	3	A request to obtain LSAs from neighbor routers, sent during the state of exchange, Loading, or Full.
LinkState Update	4	Used at the time of flooding, to send update to neighbor routers.
LinkState acknowledgement	5	Acknowledgement that an LSA has been received.

Table 1.2: OSPF Packet Types

1.6 OSPF LSA Types

In an OSPF networks routers usually have different types of LSAs that are exchanged to describe the link states associated with a router. The main types of LSAs in an OSPFv2 protocol are described below.

1.6.1 Router LSA(Type-1 LSA)

Router LSA is usually characterized as Type 1 LSA [1].It is an LSA that describes the router's interface status and the cost associated with each link. Its flooding scope is only limited to the *area* it belongs to. While generating the router LSAs, the originators router's ID is used as the link state ID that identifies the source. Router LSA includes the entire interface that the router has with in the *area* in one single LSA packet [8].

1.6.2 Network LSA (Type-2 LSA)

Network LSA is usually termed as Type 2 LSA, generated by the DR routers on behalf of the subnet [1]. It is generated both in broadcast and NBMA networks, and it describes all the available routers including the DR within an *area*. Network LSAs are flooded only with in the *area* they belong to, and they use the DR's IP interface address as a link state ID to identify the source.

1.6.3 Summary LSA (Type-3 and Type-4 LSA)

An ABR, connected to more than one *area*, has the capability of summarizing all the routes that it has learned from one *area* and passes it to other *area*s it is connected to, inter-*area* communications [1]. Several routes information is summarized in to a single prefix to create summary LSAs. This reduces the size of the routing table or the information that should exist in link-state advertisements and LSDB. The characterization of summary LSA generated by ABRs is based on the type of the destination. If the destination is an ASBR the summary LSA generated is Type 4 summary LSA and the ASBR's router ID is used as a link state ID otherwise it is Type-3 LSA and the destination ABR's ID is used as the link state ID of the LSA [1].

1.6.4 AS External LSA (Type-5 LSA)

Route information external to the AS are originated by the ASBRs and are characterized as type 5 LSAs [1].

1.6.5 Type-7 LSA

An ASBR in NSSA flexibly accepts external route information that is characterized as Type-7 LSA and it can travel through the NSSA. The Type-7 LSA is then converted to Type-5 LSA by the NSSA's ABR to the backbone, as the LSA is routed to the rest of the network. The following table summarizes the different types of LSAs in an OSPF network**.**

Name of the LSAs	Type	Created due to
Router LSA	1	• Changes in the link status(up/down), • Changes in the link cost/bandwidth • Neighboring routers changes to/from the FULL state • The changes in the state of one of the router's that is configured as virtual links
Network LSA	2	• Changes in the Network's DR • If router itself is a DR and one of the neighboring routers changes to/from the FULL state.
Summary LSA	¾	• An intra-*area* or inter-*area* route has been added/deleted/modified in the routing table. • Newly attached router to an *area*
AS-external-LSA	5	• A router is no longer an ASBR. • An external route gained through direct experience with an external routing protocol (like BGP) changes.

Table 1.3: LSA Types [1]

1.7 Basic operation of OSPF

Basic step by step operations are involved in the OSPF network which finally results in a converged network. The steps involved are discovering neighbors, synchronizing link state database, doing route calculations and finally populating the routing table with the optimal route information.

1.7.1 Neighbor discovery

In OSPF network routers that are adjacent with each other form a neighbor relationship, in order to exchange routing information and maintain that relationship after the formation of the adjacency [1]. Such adjacency formation requires directly connected routers, and the interfaces used to be within the same a*rea*.

In an OSPF network the *hello* protocol is used to dynamically discover neighbors and keep an eye on them once a neighbor relationship is formed. The *hello* protocol also helps to elect the DR and BDR to which each OSPF router should make adjacency with [1].While trying to establish fully adjacent neighbor relationships, OSPF neighbor routers goes through different states: Down, Attempt, Init, and 2-Way, Ex-start, Exchange, Loading, and Full.

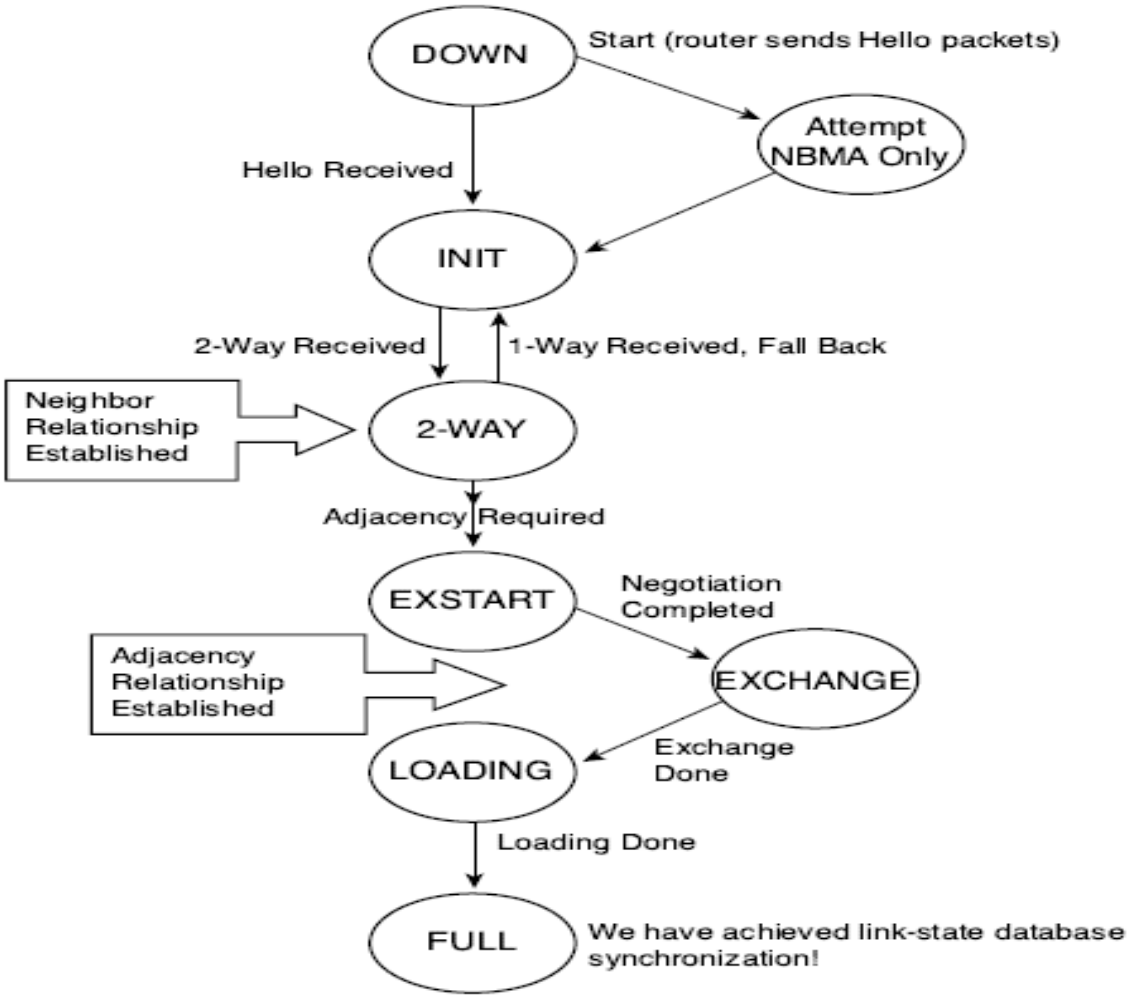

Figure 1.6: OSPF Neighbor States Types [4]

- **Down State:**

It is the first or initial neighbor state in which no *hello* control packets have been received from another node/s, no neighbor discovery yet. Down state can also result from tearing down a full state where neighbors did not hear about each other within the RDI.

- **Attempt :**

The attempt state is for manually configured neighbors in NBMA networks, a Unicast *hello* packet is sent to idle neighbors from which *hello* packets are not received within the RDI.

- **InitState:**

InitState is a state in which a *hello* packet is received from a router that is trying to establish a neighbor relationship. In this state, the *hello* packet received by a router does not contain the

receiver's router ID .The receiver node is expected to include the sender's ID in its *hello* packet as an acknowledgement that a valid *hello* packet has been received by it.

- **2-Way state:**

It is a state that follows the InitState in which a bi-directional communication is established between two routers. This state is achieved when the receiving node finds its own router ID inside the *hello* packet sent by another node; both routers have seen each other's *hello* packets at this stage and they are considered as neighbors. DR and BDR are elected for broadcast and non-broadcast networks. A router becomes full state only with the DR and BDR and stays in a 2-Way state with all other neighbors. But, on a point-to-point or point-to-multipoint networks a router becomes in full state with all connected routers in the network.

1.7.2 Database synchronizations

- **Exchange start (Ex-start) state:**

Once the DR and BDR are elected in the 2-way state, routers start to exchange link state information with their DR and BDR which transit it to Exstart [3]. In this state router establish a Master-Slave relationship on a neighbor basis and chooses the initial sequence number used for the DBD packets to be exchanged among them [3]. A router is elected as Master on the basics of its router ID.

- **Exchange state:**

The Ex-start transits to the Exchange state once the Master-Slave and sequence number is negotiated between adjacent neighbors. In this state, neighbors exchange database description packet that describes their database [8]. The database description packet contains only the LSA header that describes the content of their LSDB. The database description packet sequence number is incremented only by the Master and it has to be acknowledged by the slave in explicit manner [8]. In the process of Exchange state, routers can also send and receive link-state request and update that contains the entire LSA .After database information has been exchanged among neighbors, the Exchange state can change to Loading or Full state.

- **Loading state:**

Loading state is when the Link state request list is not empty. Based on the information provided in the database description packets, routers make a request for link state information they don't have .The requested router responds with a Link State Update packet that contains the information being requested and this update is also acknowledged by the receiver. When the exchange process is completed between neighboring routers their state transfers to the Full state.

- **Full state:**

It is considered as the fully functional state of OSPF neighbors where the Link state request list is empty and neighbors are fully adjacent with each other. The following figure illustrates the different types of OSPF message exchanges from adjacency start-up to completion.

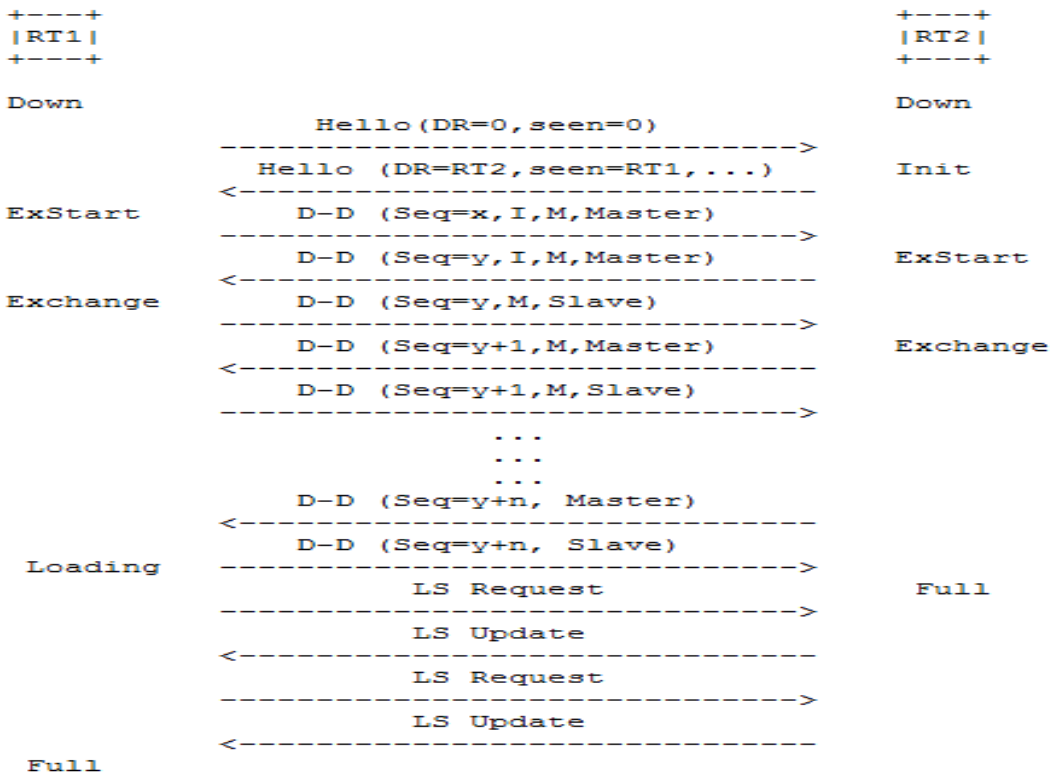

Figure 1.7: an adjacency bring-up example [1]

1.7.3 Route calculations

Once link state information is synchronized among routers, each router in a network performs a route calculation. The route calculation is based on the SPF (Shortest Path First) algorithm that chooses an optimal path between nodes. The outcome is optimal routes that are populated in the routing table and placed on the forwarding table [3] [1]. The interface reach-ability and the cost metric are the factors in which the route calculation is based on. Cost on interfaces can be set by a network administrator or can be derived from link characteristics, and the lowest cost metric is chosen as the optimal one. Up on later changes once a converged network is achieved, neighbors send an immediate update to reflect the change that occurs in the network status. This makes other OSPF routers to change their state .The update only carries the change that occurred, and each router that receives the update goes through the synchronization process to achieve the same database, there by achieving convergence in the network.

1.8 OSPFv2 timers

In the RFC 2328 several OSPFV2 parameters have been described as architectural constant values and some are listed as configurable. Earlier OSPF implementations are based on the RFC 2328 but nowadays there are several OSPF parameters that are vendor specific as well.

1.8.1 OSPFv2 Architectural Constant Timers ,RFC 2328

Name	Time value	Descriptions
LSRefreshTime	30 minutes	Time in which a router generates a new LSA, as the LS age field of one of its LSA reaches the value *LSRefreshTime*.
MinLSInterval	5 seconds	The minimum time between distinct originations of any particular LSA.
MinLSArrival	1 second.	It is the minimum time that must elapse when receiving new LSA during flooding; LSA received without this interval is discarded.
MaxAge	1 hour	It is the maximum age that an LSA can reach. When an LSA's LS age field reaches *MaxAge*, it is re-flooded to flush the LSA from the routing domain. Such LSAs are not important in the routing calculation.
CheckAge	5 minutes	It is the time interval in which an LSA's checksum is verified as LSAs, which reside in LSDB, reaches multiple of *CheckAge* interval.
MaxAgeDiff	15 minutes	Due to the nature of the topology in the network, similar LSAs with the same sequence number but different ages may be received twice or more at some router. This will make the receiver node inefficient to assume that the LSA is different than it has already received in the flooding process. As a result, OSPF assumes such LSAs to be different only if the age differ more than the *MaxAgeDiff* interval.

Table 1.4: OSPFv2 Architectural Constants Timers [1]

1.8.2 OSPFV2 Configurable timers, RFC 2328

Name	Time value	Description
RxmtInterval	5 seconds (default for LAN)	It is the transmission time interval in which an unacknowledged LSA can be re-sent. It should be more than the expected round-trip delay between any two routers on the attached network to avoid unnecessary re-sending.
InfTransDelay	1 sec	It is the amount in which an update LSA should be incremented at a router's interface, during flooding. It must be greater than 0 and the sample value for a local *area* network is one second.
HelloInterval	30 /10 sec	This is the time interval between two successive *hello* packets. Sample value for non-broadcast networks is 30 seconds and that of a LAN is 10 seconds.
RouterDeadInterval	4*(*HelloInterval*)	This is the time interval that a router uses in conjunction with its *HelloInterval* to detect the inactivity of its neighbor. This value must be the same for all routers attached to a common network.

Table 1.5: OSPFV2 configurable parameters [1]

1.8.3 Vendor Specific timers (Cisco)

Vendor	Parameter name	Values	Descriptions
Cisco	SPF initial delay	0-65535sec (5 sec default)	It is the initial delay from LSA reception until the first SPF is computed.
Cisco	SPF hold time	0-65535sec (10 sec default)	Time between two successive SPF calculations Time between two successive SPF calculations. Zero sec, no delay between successive SPF.
Cisco	Flood Pacing Timer	5-100msec (33msec default)	Determines the rate at which LSAs are flooded.
Cisco	Retransmission Pacing Timer	5-200 msec 66 msec(default)	Delay before resending unacknowledged packet send to neighbor**.**
Cisco	The OSPF LSA group pacing	10-1800sec (240 sec)	Applies for grouping LSA for refreshing, check summing, and aging functions (Cisco IOS Release 11.3 AA).

Table 1.6: OSPF Specific Timers, Cisco.