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Dynamic Metric in OSPF Networks

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DYNAMIC METRIC IN OSPF NETWORKS

DYNAMICKÁ METRIKA V OSPF SÍTÍCH

Zkrácená verze Ph.D. Thesis

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INTRODUCTION

The exchange of different types of information is essential today. The networking technologies have leaked into many people's lives and many innovations have been made in networking and transmission technologies. Larger networks contain multiple network devices like routers that need to forward data effectively and dynamically. Routing is at the core of networking and Internet technology and cannot be completely separated from any other network processes. The path chosen may be the shortest in the topology graph but the high network traffic can make the quality of service served to the users insufficient. Therefore initial research in routing with consideration of traffic optimization is needed.

Since OSPF represents one of the most widely used routing protocols, any valuable improvement to keep pace with the rapidly changing Internet environment would be greatly appreciated. The limitation of this protocol is that its link cost calculation algorithm does not take actual link load into consideration. OSPF is not traffic aware. The traffic of individual flows may change over time, possibly leading to a situation where some links carry mostly idle connections and others are congested. The OSPF metric is static what causes bottlenecks in the path.

This thesis proposes a novel approach intended for real-time, dynamic detection, measurement and analysis of changes of the network traffic in a way that relieves congested links and splits the traffic in multiple paths of the network if possible. The proposed path determination is based on the utilization of the individual links at that point in time. This method offers an approach of more efficient path usage as the bandwidth requirements grow and provides wished traffic-aware routing.

In order to ensure real-time dynamic control of processes such as occurrences of events in networks, Exponentially Weighted Moving Average technique was applied. For this thesis, detected raw data are link load observations of routers. Link load values represent data from which the moving average is computed.

Moreover, the shortcomings of default OSPF protocol are illustrated on a simple testbed. The OSPF routing system deployed for this testbed uses the shortest path routing algorithm without any improvements. Test results confirm the bounded characteristics of OSPF, especially the absence of traffic awareness.

Several simulations in Matlab are performed to verify the behavior of method before deployment to real devices and to ease the testing and development of projected changes to the OSPF protocol. Simulations are used to explore and gain more insides into the new model. After the predicted behavior of improved routing in OSPF networks is validated by the simulations, practical examination is deployed. The goal is to test some main scenarios covering all possibilities. Then compare default OSPF and proposed mechanism based on values resulting from tests performed in real network environment.

1 STATE OF THE ART

The critical point for modern telecommunication networks is the distribution of services over a global communication network. For the successful communication between systems and the provision of quality of service, a communication control needs to be fulfilled. Such a control is achieved by a deployment of hierarchical model of communication. The thesis focuses on the efficient selecting of a path and moving data units across that path from a source to a destination providing by the Internet layer. One of the most important functions of the Internet layer is a routing.

Routing is one of the main procedures of the Internet and enables establishment of robust and efficient network. Routing is a method of finding a path and forwarding packets across that path from a source to a desired destination. Routers interconnect networks and pass packets from one to the other. Destination networks are added to the routing table using either a dynamic routing protocol or by configuring static routes. Dynamic routes are learned automatically by the router using some dynamic routing. The behavior of routers depends on a routing protocol. A routing protocol defines a set of rules used by a router (or any other entity that performs routing) for communication with neighboring routers. Routing protocols provide the format of sent message, the process of sharing information about the path, the process of sending error messages and initialization and termination of session and dynamic routing table management.

1.1 Open Shortest Path First

The thesis focuses on OSPF specified in RFC 1131 [1]. The current version of OSPF Version 2 is specified in RFC 2328. OSPF is the most widely used link state protocol classified as an Interior Gateway Protocol. The protocol uses a method based on Dijkstra's algorithm that solves the shortest path problem [2]. The algorithm dynamically determines a path of minimal total cost between the nodes. It allows routers to be selected dynamically based on the current state of the network. The OSPF metric indicates the relative cost of the link. It is often inversely proportional to the bandwidth.

To illustrate the shortcomings of OSPF protocol in detail, simple testbed for experimentations is created. The physical layout of the test network with default OSPF routing algorithm is shown in Figure 1.1. The picture of configuration of routers is shown in Figure 1.2. For instance, if there are two links with the same bandwidth and the utilization of the first link is very low and for the second link very high, OSPF assigns both links the same metric. Most of the routers are connected with Fast Ethernet link which corresponds to the cost of 1. Based on the composite metric, calculated as a sum of individual metrics on the path to the destination, the entire data traffic passes the link between Router D and Router E. There is no traffic on paths from Router B to Router E and from Router I to Router E. The reason is simple. Current OSPF characteristic leads to use the shortest path, which means the path from Router D to Router E. With increasing users' demands on the servers, a particular part of the network, the link between Router D and Router E, may become congested. Such congestion causes performance degradation and in some cases also service disruption.

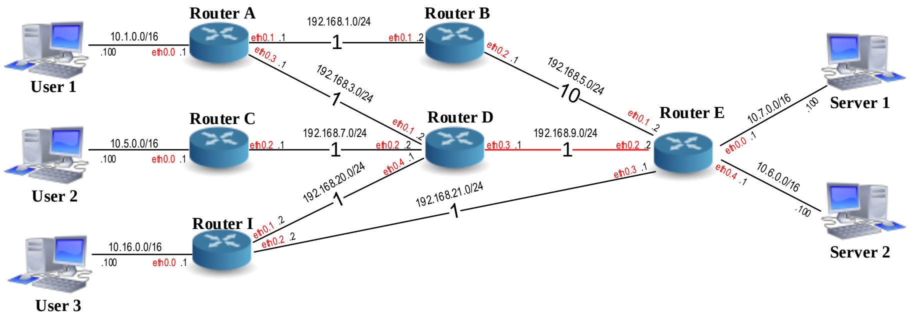

Figure 1.1 Testbed with default OSPF routing algorithm

Figure 1.2 Configuration of routers in testbed with default OSPF routing algorithm

The chosen type of router is Linksys WRT54GL version 1.1. Its firmware is based on Linux. However, the firmware directly installed to the router is not open for testing. The firmware is not open-source and no modifications can be done. For the usage of basic router's functionality, the original Linksys firmware is fine. However, for the purpose of this thesis, a third party firmware supporting extra functionality has to be considered. GNU/Linux distribution called OpenWrt is used. Quagga represents a routing software offering implementations of routing protocols such as OSPF. The ospfd daemon supports the OSPF version 2 protocol [16].

There is a standard method for configuring and monitoring IP protocols with the help of the Simple Network Management Protocol (SNMP) [17]. SNMP detects the increasing number of packets coming through one of the router's interface, suggesting that the interface is about to get congested.

Default OSPF is tested on the testbed. The next section presents a series of fundamental graphs related mainly to the utilization of the devices. Measured data are captured with the help of PRTG monitoring tool. The goal is to gradually increase the load of traffic on servers. In this scenario, each five minutes new amount of traffic is generated on the users and sent to the servers. The observation interval is set to 30 minutes. The behavior of default OSPF routing process is shown in Figure 1.3. There are three interfaces connecting different routers - interface eth0.1 connecting Router B, interface eth0.2 connecting Router D and interface eth0.3 connecting Router I. Since the shortest path from User 1, User 2 to Server 1, Server 2 passes through Router D (eth0.3) and Router E (eth0.2), this link may become highly utilized. From the graph can be seen that there is no traffic on interface eth0.1 and eth0.3 of Router E while interface eth0.2 is utilized.

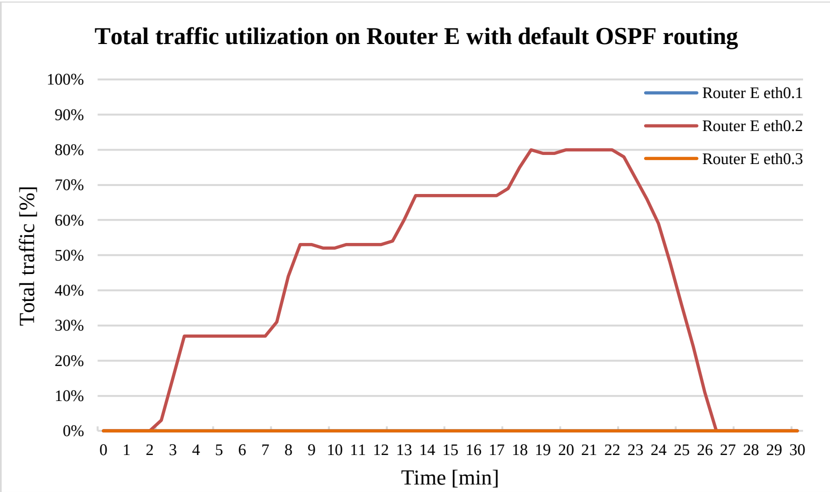

Figure 1.3 Total traffic utilization on Router E with default OSPF routing

All the traffic from users to servers passes through the interface eth0.2. On the other hand, the bandwidth of remaining two links, which can carry the traffic but are not allowed to, is wasted.

Some attempts to provide improved routing were proposed in the past. The recent works related to routing algorithms improvement [9], [10], [11], [12] can be used to choose a path with specific bandwidth requirements. New Cost Adaptive OSPF (CA-OSPF) is proposed in [8]. However, this solution is not applicable for heavily loaded networks where the CA-OSPF cannot improve the network performance. An implementation of QoS routing extensions to the OSPF is proposed in [13]. Also some balance heuristics were proposed to avoid congestion and utilize low loaded links [14], [15]. However all of these solutions focus only on the case of full link congestion and there is no rerouting of traffic until the congestion appears. Also, if the demands on traffic changes rapidly, another approach is needed. Finally the convergence is reached when this load balancing gets to a stabilized state, but the convergence time is very long, reaching link congestion a few times on different links in the process. This equilibrium is again broken when the amount of traffic changes and convergence process has to start all over.

1.2 Next-Generation Networks

Increasing requirements for personalization, consumer's mobility and agile services call for a new communication environment. Consumers are looking for easier and better ways of reaching out to each other over whatever terminal or access technologies, which are available at the moment. Users want to share their latest experiences anywhere and anytime, therefore the network infrastructure must provide sufficient network resources for high-value services. A natural way to fulfill these demands is the evolution towards an all-IP environment which appears to be a strong trend. This trend converges towards a Next-Generation Network (NGN) specified in ITU.T Y.2001 [4]. Various views on NGN have been expressed, however, the heart of the NGNs forms an IP-based network.

IP Multimedia Subsystem (IMS) represents such an architecture providing multi-access to required services and large-scale interoperability. The idea of IMS is to integrate traditional telecommunication services with the Internet Protocol. Therefore, this architecture uses two of the most successful representatives in communications, namely fixed/mobile networks and the Internet. The IMS technology originated from the Third Generation Partnership Project (3GPP) Release 5 specifications [5].

In spite of cellular networks providing mobility and a wide range of services, the main reason for creating IMS is to offer more than the mere Quality of Service (QoS) support. The term QoS is widely used in the telecommunication world today. All IMS solutions should guarantee the QoS that customers need and demand. Deployment of the new services depends on the QoS level that the IMS technology is capable to provide.

Since the IMS involves a large amount of protocols, it is important to define ways in which different end system can reach the end-to-end QoS for a connection. One of the questions is how to use lower layer QoS mechanism to achieve upper layer QoS within the network. There is a need to ensure the interoperability among different layers, domains and networks. The network capacity is currently adequate for the majority of applications. In spite of that, it often happens that the user's perceived qualities of network traffic characteristics are not satisfactory. To provide end-to-end QoS, it is necessary to manage the QoS within each domain along the path [23], [24], [25], [26].

In the IP domains, there are some well-known mechanisms for QoS provisioning, such as Differentiated Services (DiffServ) and Integrated Services (IntServ). The utilization of these mechanisms in the IMS is still an open issue. The end-to end QoS in the IMS architecture introduces several challenges which have to be faced [21], [22].

2 THESIS OBJECTIVES

Modern routing domains need to maintain a very high level of service availability but with the growing demands of users, the data networks may become heavily loaded and data links congested. Such congestion causes performance degradation and in some cases also service disruption. OSPF networks are often heavily loaded which leads in redundancy in the form of network devices or communication mediums installed within the infrastructure. It is a method of ensuring network availability and continuity of services in the case of unplanned failure. In complex networks, it is often that similar or almost equivalent paths exist toward a destination. Thus, the mentioned alternative paths may provide a potential in order to balance traffic in the best way between multiple paths. The question is how to balance the network traffic between various paths when the particular link becomes heavily loaded.

The main goal of the thesis is to propose, verify and analyze more efficient mechanism to improve routing in OSPF networks. To achieve this purpose, a new complex solution that extends current methods of the OSPF routing is examined. A novel approach to calculate OSPF metric will split the traffic from the congested links in multiple paths, if necessary, according to involved logic. The method considers link load as an additional parameter for a final metric calculation. This solves the problem of absence of traffic awareness and inconveniently congested links; what decreases network utilization and increases network performance.

The goal is to keep the traffic load on all links at acceptable levels if it is possible from the network infrastructure point of view. To realize the main goal of the thesis, some partial aims need to be accomplished that are summarized in following points:

- To perform detailed analysis of routing protocols, especially OSPF, and adopt all its features and principles.
- To illustrate the shortcomings of OSPF protocol, simple testbed for experimentations will be created.
- To propose a novel method for link load sensitive metric strategy. The proposal will be based on mathematical functions leading to improve routing.
- The method proposed will be investigated in Matlab environment. The collected data from simulation sets will be analyzed and evaluated.
- To transfer the theoretical plane into practical form and to allow transparent and replicable testing of method proposed, a testbed will be used. This environment will correspond to simulated network structure. This procedure will ensure compatibility and prove theoretical expectations.
- To prove and verify the benefits of new method. The data collected during simulations and experimental testing will be compared, analyzed and evaluated.

3 PROPOSAL OF A NEW ROUTING METHOD

The efficiency of packet switched network communication depends on the ability of routers to determine the best path to send and forward packets to desired destination. The idea is to find a method extending OSPF with the purpose of achieving more effective solution to the routing optimization problem.

Determining the best path for a packet involves evaluation of multiple paths (if available) to the same destination and selection of the most suitable one to reach that destination, possibly on the per flow basis. OSPF provides support for mentioned multiple paths to the desired destination. The advantage of multi-path algorithm is that it can provide better throughput and redundancy. Preferred load balancing algorithms use bandwidth information to distribute the traffic over more of router's ports. There are two types of load balancing: per-flow and per-packet. Per-flow load balancing distributes the packets according to the addresses while per-packet load balancing generally uses round-robin technique.

When two or more routes to the same destination have identical metric value, a router load balances between these paths. The procedure is called equal cost load balancing. This technique splits the traffic to multipath destination quasi-equally between all the equal metric paths. If a router discovers multiple paths to a destination, the routing table is updated and contains one destination network but multiple exit interfaces, one for each equal cost path.

Equal cost multipath load balancing is a significant improvement over a single path routing. On the other hand, it is not the final solution to the traffic optimization problem. This is where improved techniques are needed. The algorithm determines the path of minimal total cost between the nodes based on the bandwidth parameter. However, the default OSPF routing behavior does not consider the current link load as described in chapter 1.1. The proposed path determination is based on the utilization of the individual links at that point in time. This method offers an approach to more efficient path usage as the load requirements grow. The purpose is to relieve the congested links and split the traffic between multiple paths supporting load balancing, if there are any. The aim is to set link metrics to keep the traffic load on all links at acceptable levels. A new routing mechanism called DM-SPF (Dynamic Metric - Shortest Path First) is introduced. Initial thoughts related to the method are described in [18], [19] and [20].

3.1 DM-SPF (Dynamic Metric – Shortest Path First)

Proposed routing protocol is a set of processes, algorithms and messages used for the deployment of dynamic metric in OSPF networks. The idea is to create a solution to traffic optimization problem to prevent network performance degradations and congestions. The purpose of this method is to gradually adapt the routing to the changing conditions of a network. The method basics are summarized as follows:

- Routers process additional information about the state of links related to current load, over general OSPF.
- Overloaded links initialize rebalancing of the traffic between multiple paths, if there are any such paths.
- New routing tables with new quasi-shortest paths are computed based on the load information.
- The traffic is sent through newly calculated paths, with the intent to reduce the load of overloaded links.

Sending packets through a single path is not the most efficient use of available bandwidth. Instead of passing the traffic to the overloaded link, the routers according to DM-SPF will take into account the link load and try to find less loaded concurrent paths for load balancing. Paths with equal metrics to the same destination may share the load in a per-flow fashion. To ensure that the packets are routed via the best possible paths, an additional information describing the load of various links combined into the metric, is attached. An integer value is assigned for the load of a link as an additive component to the bandwidth based metric. The load statistics are computed using the interface counters generally available for SNMP purposes.

The purpose of DM-SPF distributing the traffic among multiple paths to the same destination is to use available bandwidth more efficiently. The goal is to reduce the amount of transferred packets when links are under a significant traffic load and to avoid any critical bottlenecks.

3.1.1 DM-SPF routing protocol principles

The DM-SPF principle is described in Figure 3.1. In the figure, each path is labeled with a value of its cost. If a user communicates with a server, the entire data traffic passes the Link A, marked red. The metric of the shortest path is 1. There is no traffic going through Link B and C. Under moderate traffic, the utilization is acceptable and no changes are needed. Under heavy traffic, more than 90%, the network behavior significantly changes from routing point of view. According to DM-SPF, overloaded router initializes rebalancing of the traffic between multiple paths. DM-SPF runs the process of finding next suitable path with the lowest metric. The possible path to pass the traffic is Link B and C, so far used as standby links, with the composite metric of 2. It can be seen that the path is not the path with the minimum number of hops. To ensure that the traffic will be balanced between two paths, the cost of overloaded Link A must be increased by 1. After the change, two paths from the user to the server have the same metric of 2. That forces the routers to insert multiple paths to the destination into their routing tables. It means that DM-SPF manipulates the routing process in order to achieve load-balancing. If there are no other suitable paths for load balancing to be found, the routing situation remains and no changes are made. If the network traffic becomes low, less than 10%, the affected router is triggered to use standard OSPF path metric calculation.

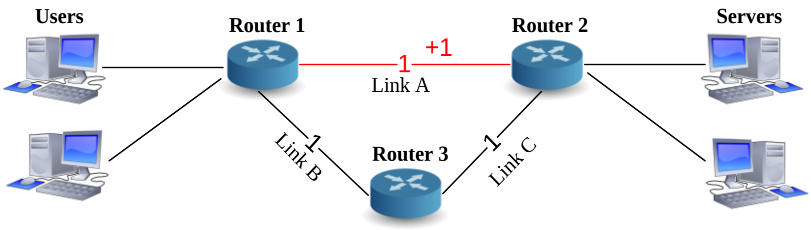

Figure 3.1 Simple DM-SPF explanatory network

After the change, all routers must agree on the network topology and achieve routing convergence. Having explained the introduction how DM-SPF works, what remains is to describe the new metric calculation.

3.1.2 A novel metric calculation

The OSPF RFC 2328 [2] does not specify what the link metric should be. The assignment of link metrics is left up to network administrators. Most of the routers (Cisco routers e.g.) calculate the metric from link bandwidth. The metric is then inversely proportional to the bandwidth. A higher bandwidth results in lower metric. The formula used to calculate the metric of one interface is:

$$OSPF\ metric = \frac{reference\ bandwidth}{bandwidth}. \tag{3.1}$$

Link metrics do not include the link load. The idea is to consider link load as an additive parameter. Solution is that an integer value representing the load of a link is used as an additive component of bandwidth based metric. Together with default cost, the additive metric value reflects the current load of the link so that the routing table contains accurate optimal path information. The novel metric is then based on multiple characteristics of a path - bandwidth and link load. The path selection is then influenced by preferring the path with the highest bandwidth while considering the traffic utilization of a certain link. It means that the novel method bases route selection on multiple submetrics, combining them into a single metric.

If load is to be used as part of a composite metric, DM-SPF must not allow sudden changes in link traffic in order to destabilize the network. The goal is to avoid the impact of unexpected and accidental peak utilization. Such a burst of heavy traffic could trigger an update.

Since the link load is a dynamic variable, moving average is used for the metric calculation. For this thesis, the used raw data are link load observations of routers. Link load values represent data from which the moving average will be computed.

For the purpose of DM-SPF, Exponentially Weighted Moving Average (EWMA) [6] is used. EWMA uses weight factors that decrease exponentially. It means that the weight of each older observation decreases exponentially which brings more importance to the recent observation. Let c_t be an observation at time *t*, the explicit formulation of EWMA is:

$$EWMA_t = \lambda c_t + \lambda(1-\lambda)c_{t-1} + \lambda(1-\lambda)^2 c_{t-2} + \cdots + \lambda(1-\lambda)^{t-1}c_1 + (1-\lambda)^t c_0$$

$$= \lambda \sum_{i=0}^{t-1} (1-\lambda)^i \, c_{t-i} + (1-\lambda)^t c_0 \tag{3.2}$$

where $EWMA_t$ represents the exponentially weighted moving average of all past observations with the weights decreasing exponentially. The starting value c_0 equals 0 or is generally being set to the mean of former observations. The effect of the starting constant c_0 decreases as time increases. The formula relies on an effective period for the exponential moving average called weight or smoothing factor λ where $\lambda = \frac{2}{n+1}$ and n is the period of the moving average. The parameter λ determines the rate at which older data enter into the calculation of the EWMA and has dynamic range of $0 < \lambda \leq 1$. The value of $\lambda = 1$ implies that only the most recent observation influences the EWMA. Thus, a large value of λ gives more weight to recent data. The weight of all the older observations is then decreased by the factor (1- λ) [6], [7].

Exponentially Weighted Moving Average can be computed recursively as [6]:

$$EWMA_t = \lambda c_t + (1-\lambda)EWMA_{t-1}. \tag{3.3}$$

The recursive form of the EWMA calculation simplifies the formula (3.2) and decreases processing and memory demands on computing devices which is important for implementation into real devices with little spare resources. The recursive fashion (3.3) requires only two pieces of information to be processed. The expression can be explained as follows: at time t, the EWMA equals the multiple of lambda times actual observation plus 1 less lambda times previous observation. The predictive form of EWMA is then given by:

$$EWMA_{t+1} = \lambda c_t + (1-\lambda)EWMA_t. \tag{3.4}$$

EWMA has become popular process-monitoring tool in a process-control field. Due to EWMA's robustness and ability to monitor a dynamic process with memory and drift, this approach is adopted within this thesis.

The application of the EWMA technique is demonstrated using an example depicted in Figure 3.2. The figure shows measured network utilization and the impact of EWMA on the data. The blue line stands for raw link load data, the representative of current load utilization. The red line represents the EWMA applied to the raw data with 5, 30, 60 and 300 seconds time period. It can be seen that the series are smoothed, with much lower variance. The decrease of weights is an exponential function of the weighting factor λ. Such process is demanded to avoid undesired reaction to unexpected jumps in link load.

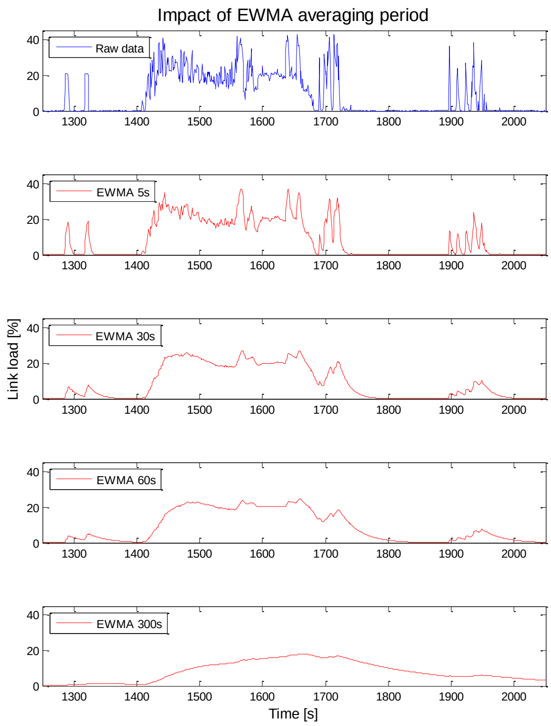

Figure 3.2 Impact of EWMA averaging period

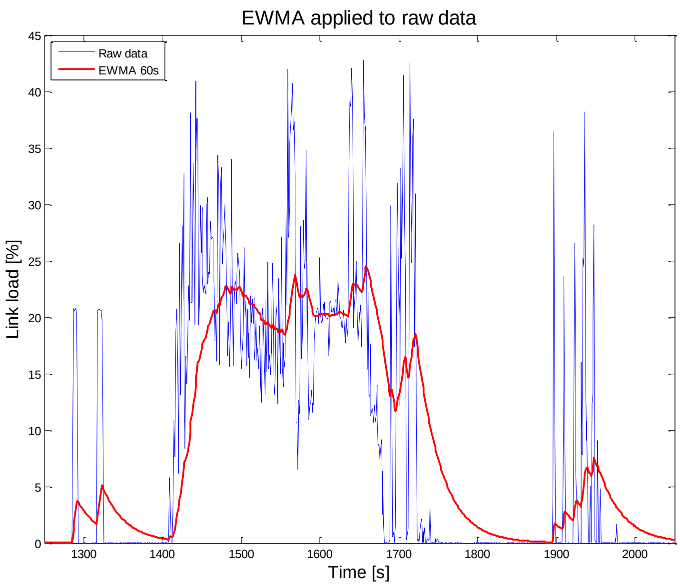

Figure 3.3 EWMA applied to raw data

The next step is to find the most suitable smoothing factor. If the value of λ is high, like in the case EWMA five seconds, only few recent observations are considered and the EWMA curve almost copies the load curve. So the parameter λ should be decreased. On the other hand, if the value of λ is close to zero, like in the case EWMA 300 seconds, the moving average is significantly influenced by older values. It can be seen that the convergence time is too long, which is not desirable. Based on these findings, the most suitable period is then 60 seconds for DM-SPF. More recent values are weighted more prominently than older values and burst traffic is filtered. The resulting graph with chosen time period is shown in Figure 3.3 in detail.

The computation of the metric for DM-SPF builds on common metric calculations used by OSPF protocol mentioned in formula (3.1). Formula (3.3) is used for EWMA computation and applied onto the metric. The resulting metric including EWMA can be then expressed as:

$$DMSPF\_metric_{EWMA}(load) = \begin{cases} metric\_init & for\ EWMA(load) < 10\% \\ metric & for\ 10\% < EWMA(load) < 90\% \\ metric\_load\_balance & for\ EWMA(load) > 90\% \end{cases} \qquad (3.5)$$

where the component $metric\_init$ initialize default OSPF protocol metric if the EWMA load of the affected router drops below 10%. The component $metric$ is a link metric computed according to the formula (3.1) and $metric\_load\_balance$ is triggered when 90% of utilization is reached.

The question is how to find alternative paths. The process of finding alternative paths includes following steps. The current shortest path (Link A) is not considered for further computations and is marked down. The next step is to apply Dijkstra's algorithm to this modified topology. After new shortest paths with new composite metrics are found, it is possible to increase original metric of Link A to demanded value.

Let's assume in the following graph in Figure 3.4 that $q(a) = 1, q(b) = 1, q(c) = 1$ where $q()$ is a function converting the edge parameter to its metric calculated according to general OSPF process.

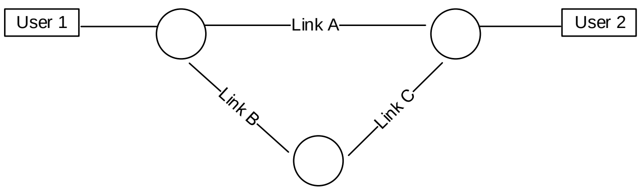

Figure 3.4 Explanatory graph (alternative path finding)

Dijkstra's algorithm is performed and chain α, which represents the shortest path to the destination, and its composite path metric q are obtained. In this case, $q = 1$ for the chain α, consisting of Link A only.

All cuts in the graph including components of the chain α have to be obtained. There are two cuts for the graph. Then for each component of the chain α, subgraphs are created. Each subgraph β_i includes the component α_i and all the edges that are part of any cut together with the component α_i and have the same metric, in case that there exist cuts consisting of not only α_i. If for any α_i there are no cuts also including other links, this component is removed from consideration. Each of the subgraphs represents possible optimization point. The next steps are performed for each subgraph. Edge from chain α has to be removed from β_i what yields δ_i. Then again Dijkstra's algorithm is ran on δ_i to get second-best alternative subpath, cost m of which will be later used as a $metric\_load\_balance$ for the original link α_i, except for the case that β_i is not a cycle. If the alternative subpath cost is equal to $q(\alpha_i)$, equal cost multipath was already used, therefore no further optimization should be done for this point and it is removed from list of possible optimization points γ. Especially, if β_i is not a cycle, $metric\_load\_balance$ equals m minus metrics of all edges from α that have to be added to β_i for it to be a cycle.

Figure 3.5 shows the behavior of DM-SPF when the alternative links (Link B and C) are not used in the beginning. The blue line stands for total measured data transmitted over both original and alternative links together (Link A). This is a situation representing default OSPF behavior. The next step is to apply EWMA, displayed in red curve. When 90% of utilization is reached, the traffic is load balanced. The black line displays resulting load on Link A. The utilization was significantly decreased what is the primary goal of DM-SPF. A part of traffic is switched to the alternative path which is displayed in green line. When 10% of utilization is reached, the alternative link is not needed any more and the original link takes the load back.

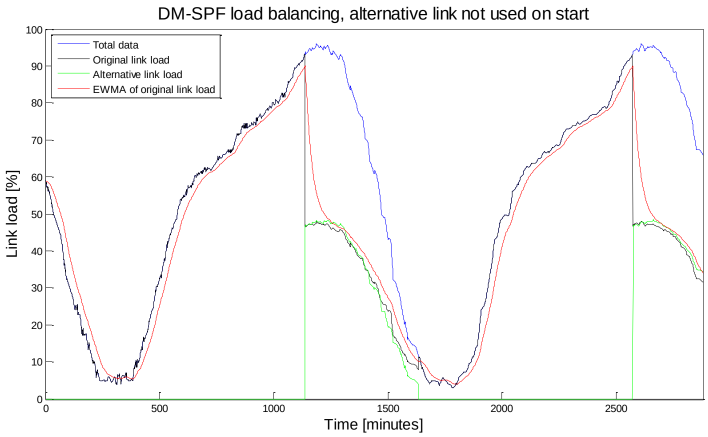

Figure 3.5 DM-SPF load balancing when alternative link is not used on start

3.2 The behavior of a router running algorithm proposed

DM-SPF describes functionality in a router that distributes packets based on improved routing information. Routers learn about the possibility of load balancing through the novel mechanism and build its routing tables dynamically and accordingly.

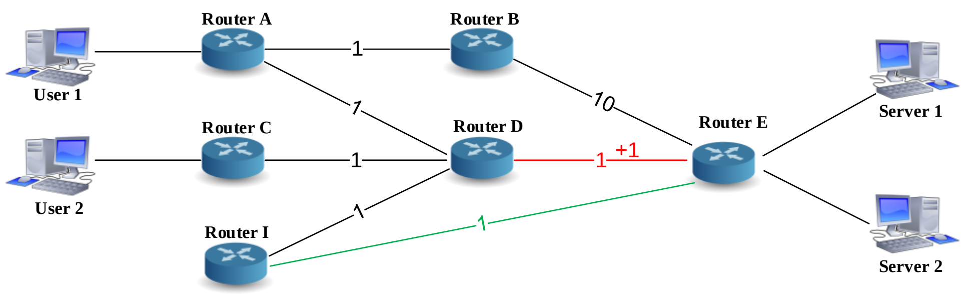

Figure 3.6 Principle of DM-SPF on testbed

Let's assume that the network described in Figure 3.6 is under moderate utilization. DM-SPF is implemented and controls the routing process according to equation (3.5). The $metric$ function is used under normal conditions. If the utilization situation changes and the EWMA of the link load reaches 90%, $metric\_load\_balance$ function is called. As mentioned before, the averaging period for EWMA is 60 seconds. The entire data traffic passes the link between Router D and Router E, marked as red link. Affected Router D detects the imminent danger.

The metric of the shortest path for Router A and C to send packets to Router E is two. There is no traffic on links from Router B to Router E and from Router I to Router E. DM-SPF triggers the process of finding alternative paths. To do so, LSDB is used due to collected LSPs. From the database, alternative path can be found. Each record in the database contains information like an interface identifier, a link number, and metric. The router has a complete map of all the destinations in the topology and the routes to reach them.

It was found that the possible link to pass the traffic is between Router I and Router E, marked as green link, so far used as a standby link. The composite metric of the whole path (Router A, D, I and Router E) equals to 3. To achieve load balancing, the metric value of the overloaded link must be increased by 1.

The process of finding alternate paths is described as follows. Dijkstra's algorithm is applied and chain α representing link between Router A and D and link between Router D and E with composite metric of two is obtained. Since link between Router A and D has no alternate path, it is not considered any more. Next step is to find cuts that split all paths from User 1 to Server 1 and include α_i as one, but not only one, of the components. There are two such cuts as described in Figure 3.7, marked red and green. Next, subgraph β_i is created which includes all edges that mentioned cuts consist of. Therefore, in this example $\beta_2 = (\text{Link D} - \text{E}, \text{Link D} - \text{I}, \text{Link I} - \text{E})$. It is worthy to mention that subgraph β_2 is a cycle. Subgraph δ_2 is created from β_2 by removing α_2, $\delta_2 = (\text{Link D} - \text{I}, \text{Link I} - \text{E})$. There is only one point of optimization because there are no other alternative paths for Link A-D. Dijkstra's algorithm is applied to the new subgraph γ_2 to get second-best alternative subpath. Cost $m = 2$ will be later used as $metric\_load\_balance$ for the original link, $metric\_load\_balance = 2$.

Before any change is done, all the routers from subgraph γ_2 has to be notified of this update. This can be done by sending DM-SPF LSA message. If the routers in question (Router I) subsequently detect link overload, they respond to this message what leads to reverting the metric to the original state $metric\_init$ even during high load.

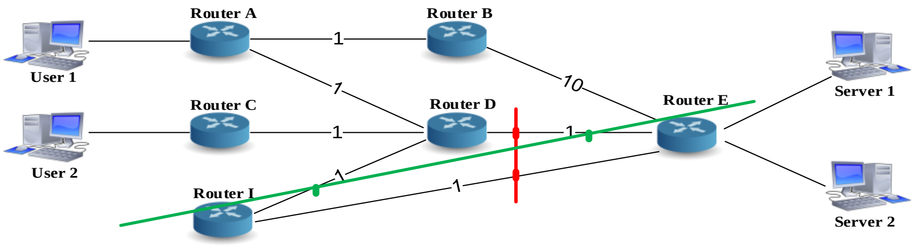

Figure 3.7 Performed cuts of the graph

DM-SPF now uses two paths to get to Router E because both paths have the same metric of 3. At this point the network is still not converged. The next step is to find the best path to each destination network. All the routers then run Dijkstra's algorithm to create an SPF tree. Once the SPF tree is completed, the routing table is created. Each router makes its decision alone, based on the information from its own routing table. For the correct functioning of DM-SPF, all the routers in an area must have complete and accurate routing information. Packets from Router D to network 10.7.0.0/16 can now use two paths with exit interfaces eth0.3 and eth0.4 allowing the load balancing of traffic.

When the EWMA of the link load decreases to 10% of utilization, the alternative link is not needed any more and $metric\_init$ function is called. In this case default OSPF routing mechanism is used to find shortest path to desired destination and to avoid the ever-growing trend of DM-SPF metric.

The convergence is achieved, the routing tables of all the routers are at the state of consistency and the routers have complete and accurate view of the network.

4 SIMULATIONS

New method needs to be tested first in order to see if the expectations were correct and if the method performs as expected before its deployment into real networks. Matlab is used for simulations. Three different scenarios are simulated. The scenarios cover the range of possible situations. The simulation of DM-SPF follows the proposal described in the previous chapter 3 and the physical layout described in Figure 1.1.

Scenario 1 consists of three parts. The goal of the first part is to rapidly increase the load of traffic on servers for short time period (burst of heavy traffic). Such trend is shown in Figure 4.1 in the first twelve minutes of measurement. The following trend is opposite. It means that the goal is to fall the load to minimum in following twelve minutes. There is no traffic generated for next five minutes.

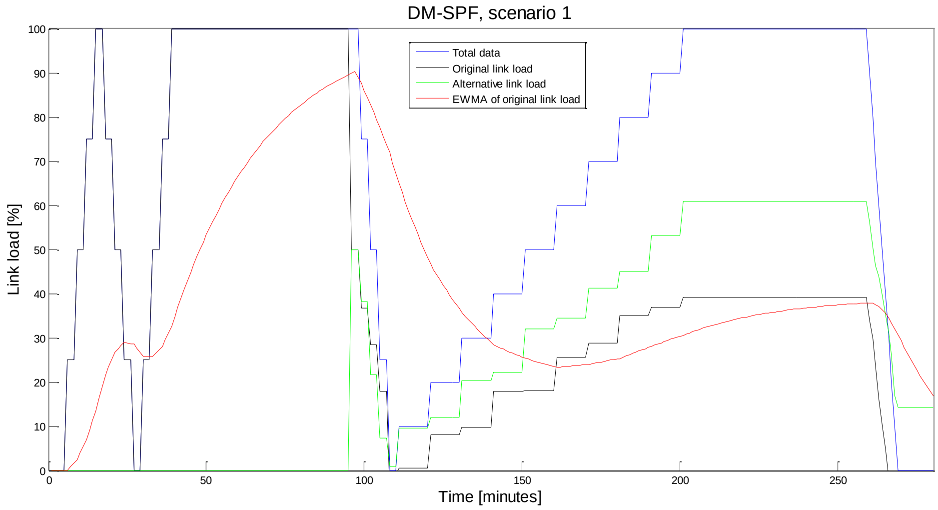

Figure 4.1 DM-SPF simulation, scenario 1

The second part follows with another rapid growing of traffic utilization. The maximal utilization remains steady over next one hour. The goal is to see if EWMA threshold of 90% is reached and load balancing process initialized. After one hour the utilization drops to zero again. There is no traffic generated for next five minutes. The third part shows a gradual increase in utilization over next 100 minutes. Over the next 60 minutes, the load remains, reaching maximal utilization. The measurement ends with final drop of utilization. The overall observation interval is set to 280 minutes.

From the Figure 4.1 may be seen that the burst of heavy traffic (first part) has no impact on DM-SPF because of applied EWMA. During the second part, the higher EWMA load threshold of 90% is reached. The total data is then load balanced between original link and alternative link. The alternate link is used because lower EWMA load threshold of 10% is not reached. The last part shows the behavior of DM-SPF while alternative link is still utilized.

In Scenario 2, DM-SPF was already used while monitoring the link utilization. It can be seen that the alternative link is in use on start. Scenario 2 consists of two parts as shown in Figure 4.2. The goal of the first part is to decrease the load to low value in the first fifteen minutes. The goal of the second part is to keep low utilization to reach the EWMA threshold of 10%. The overall observation interval is set to 60 minutes. After the load drops to very low utilization and remains unchanged, the lower EWMA threshold of 10% is reached and alternative link is not used anymore. Load is switched to the original link.

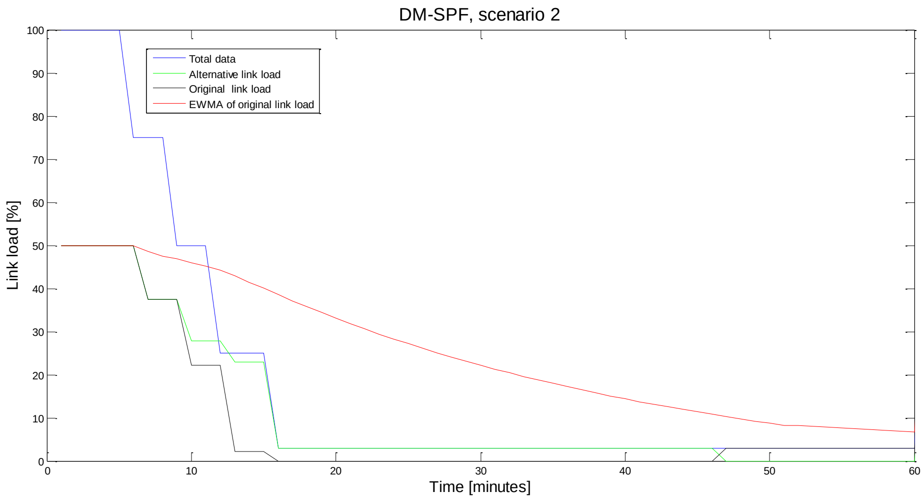

Figure 4.2 DM-SPF simulation, scenario 2

The overall observation interval of scenario 3 is set to 380 minutes. The reason is to show differences between default OSPF and DM-SPF routing mechanisms in long term interval. This scenario 3, depicted in Figure 4.3, includes two parts. The first 190 minutes time period shows the behavior of default OSPF while the following 190 minutes time period shows the behavior of DM-SPF. It may be seen that the load is balanced between original and alternative link during the second period. There is no single overloaded link.

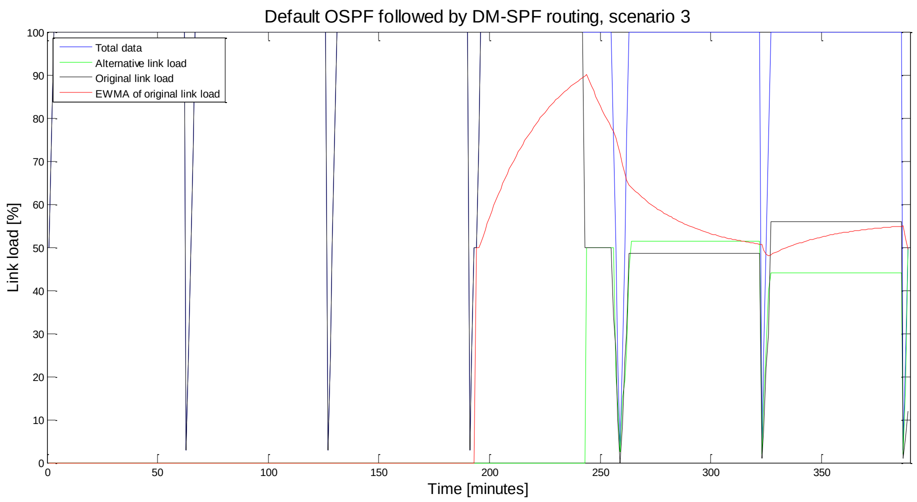

Figure 4.3 Default OSPF followed by DM-SPF simulation, scenario 3

5 EXPERIMENTAL EVALUATION OF PROPOSED METHOD IN REAL NETWORK

After the simulation and evaluation of DM-SPF using Matlab, testing in a network under real conditions follows. The routers run the trial version of DM-SPF. The network topology is described in Figure 1.1. Three scenarios are tested.

Figure 5.1 depicts total traffic utilization on Router D. The red curve outlines the utilization on interface eth0.3. The utilization on this interface follows default OSPF behavior in the first 90 minutes because *metric* function is used. Since EWMA is applied, the burst of heavy traffic has no impact on DM-SPF routing mechanism. The situation changes in minute 91. EWMA threshold of 90% is reached and the *metric_load_balance* function is called. DM-SPF initializes load balancing process, Router I is involved into routing process and traffic is balanced.

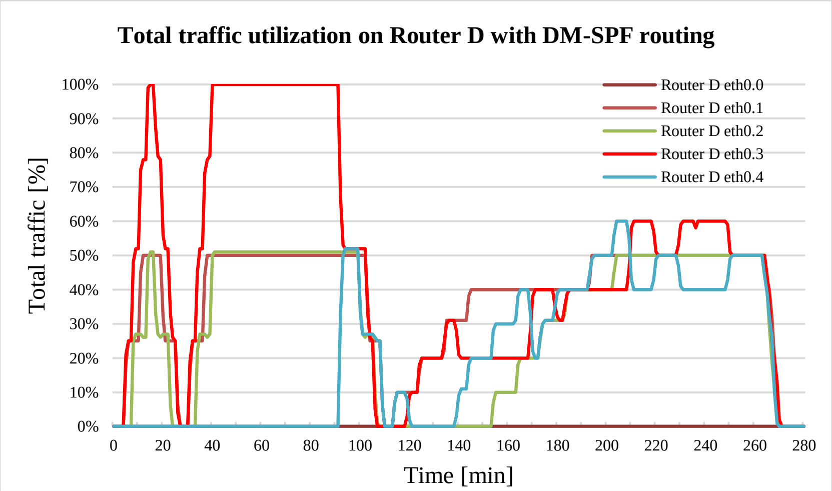

Figure 5.1 Total traffic utilization on Router D with DM-SPF routing, scenario 1

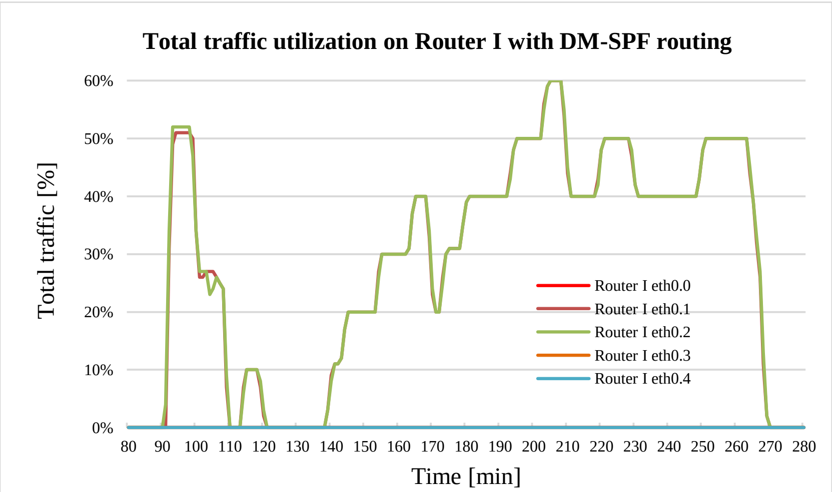

Figure 5.2 Total traffic utilization on Router I with DM-SPF routing, scenario 1

Figure 5.2 depicts the traffic utilization on Router I. There is no load on Router I before minute 91. The load is then balanced and links connected to interfaces eth0.1 and eth0.2 form the alternative path. It is important to mention that the utilization of some interfaces is almost identical and the curves are overlapping.

The second scenario describes the situation when DM-SPF load balancing is already used while monitoring the link utilization. Scenario 2 consists of two parts. The goal of the first part is to decrease the load to low value. The goal of the second part is to keep low utilization to reach the EWMA threshold of 10%. The main noticeable fact about the graph in Figure 5.3 is the traffic switch between eth0.3 and eth0.2 on Router E. If the utilization remains low and the lower threshold is reached, $metric\_init$ function is called. The load is shifted from alternative to original link in minute 40. Figure 5.4 shows the load of Router I. It can be seen that the alternative link is in use on start. There is no need to use alternative link after the minute 40.

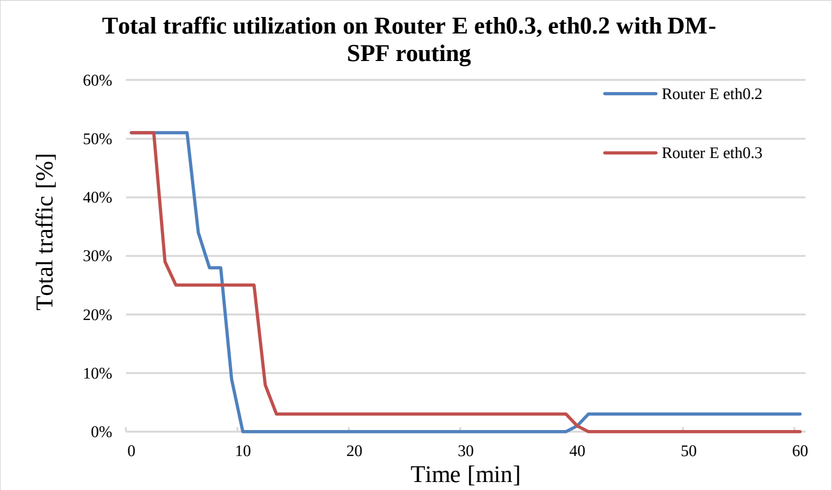

Figure 5.3 Total traffic utilization (Router E eth0.3, eth0.2) DM-SPF routing, scenario 2

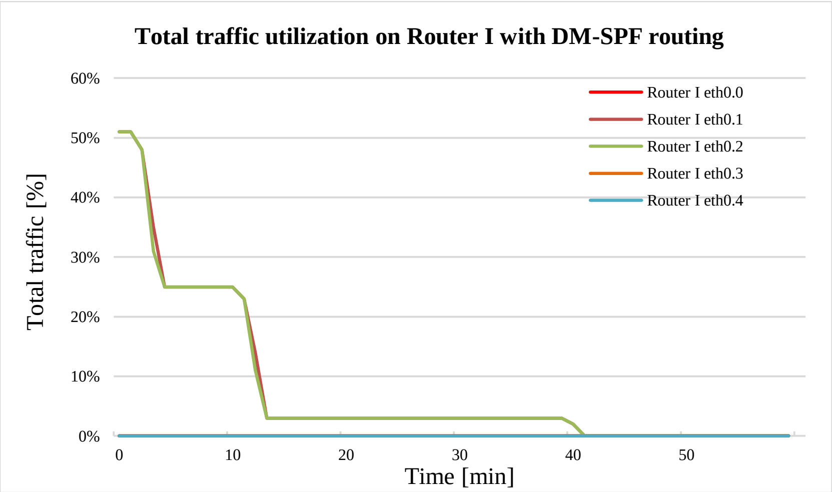

Figure 5.4 Total traffic utilization on Router I with DM-SPF routing, scenario 2

The goal of scenario 3 is to highly utilize the links and compare packet loss and coverage with and without running DM-SPF load balancing. This scenario consists of two parts. The first half of the whole observation does not run DM-SPF. The algorithm is enabled for the second half of this measurement.

Figure 5.5 shows the load balancing of traffic between eth0.2 and eth0.3 on Router E. The *metric_load_balance* function is called around minute 240. Idle interface eth0.3 is utilized after the shift. It means that the traffic is then passing Router I which is shown in Figure 5.6.

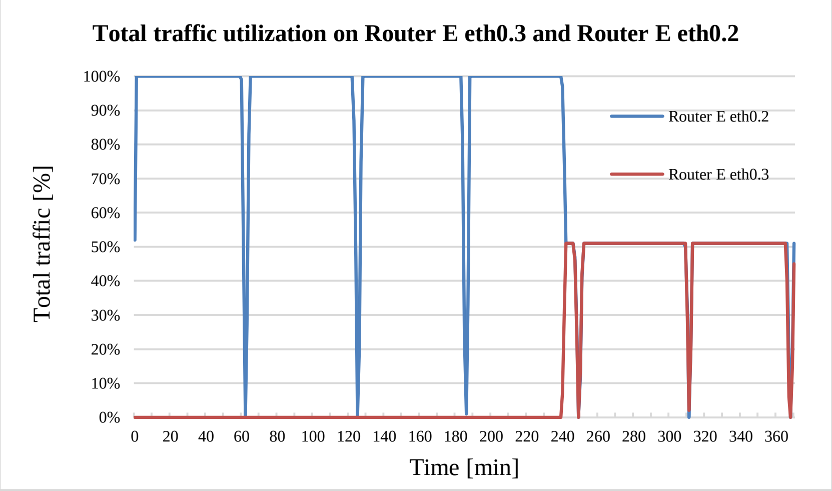

Figure 5.5 Total traffic utilization on Router E eth0.3, eth0.2, scenario 3

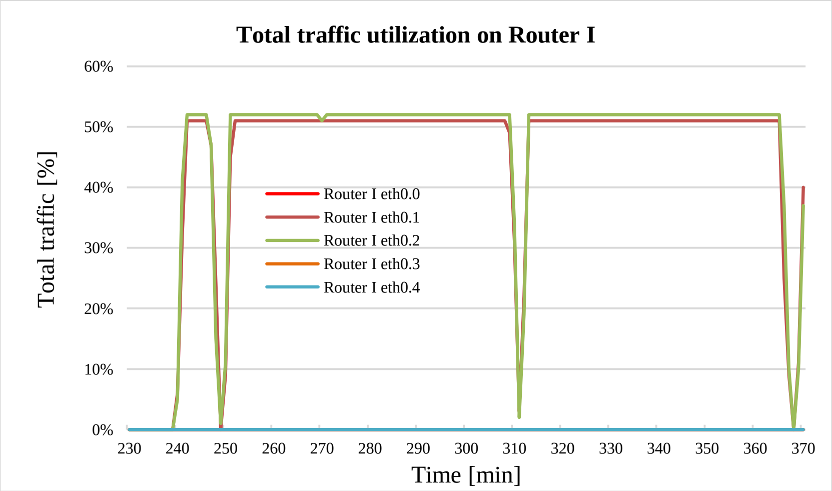

Figure 5.6 Total traffic utilization on Router I, scenario 3

6 COMPARISON OF OSPF AND DM-SPF ROUTING ALGORITHMS

This chapter focuses on DM-SPF characteristics and the comparison of default OSPF and DM-SPF method. The comparison is mainly based on values resulting from tests performed in real network environment. This chapter summarizes results from monitoring packet loss and coverage of scenario 3. There is no need to focus on scenario 2 because the load balancing is already used while monitoring the link utilization. Advantages and also disadvantages of DM-SPF are highlighted.

6.1 DM-SPF advantages

The main advantage is that the method proposed takes current link load into consideration. This approach gives an advantage of congestion avoidance and reduces its data rates in the case of congestion. The network performance is improved by supporting load balancing across parallel links. The result is that DM-SPF distributes the traffic among multiple paths to the same destination to use bandwidth efficiently.

There are some common advantages coming from OSPF. DM-SPF supports scalability and the growing of a network. It automatically adapts to topology changes and is indifferent to the network size.

Two main parameters called coverage and packet loss are observed. The term coverage stands for the ability of monitoring system to get reliable and complete data from all the monitored devices. Packet loss is chosen as an indicator of congestion and highly utilized devices. Default OSPF routing under high utilization caused packet loss, low throughput and no response to traffic congestion.

Packet loss and coverage measurements of scenario 3 are summarized in Table 6.1. It can be concluded from the conducted measurements that in specific cases not addressed by original OSPF, the DM-SPF approach decreases packet loss, increases coverage values and brings improved performance. The load balancing process starts around minute 240. Figure 6.1 illustrates the packet loss before and after the load balancing. It can be seen that routers running DM-SPF are not heavily utilized which leads to no packet loss.

Table 6.1 Comparison of default OSPF and DM-SPF routing algorithm, scenario 3

Device	Scenario 3			
	Coverage		Packet Loss	
	Default	DM-SPF	Default	DM-SPF
Router A	98.38 %	100.00 %	2.07 %	0.00 %
Router B	98.38 %	100.00 %	0.91 %	0.00 %
Router C	97.57 %	100.00 %	1.99 %	0.00 %
Router D	98.65 %	100.00 %	2.78 %	0.00 %
Router E	97.84 %	100.00 %	2.95 %	0.00 %

Router I	98.65 %	100.00 %	0.54 %	0.00 %
User 1	98.92 %	100.00 %	1.74 %	0.00 %
User 2	98.38 %	100.00 %	1.95 %	0.00 %
Server 1	99.59 %	100.00 %	0.17 %	0.00 %
Server 2	98.65 %	100.00 %	1.00 %	0.00 %

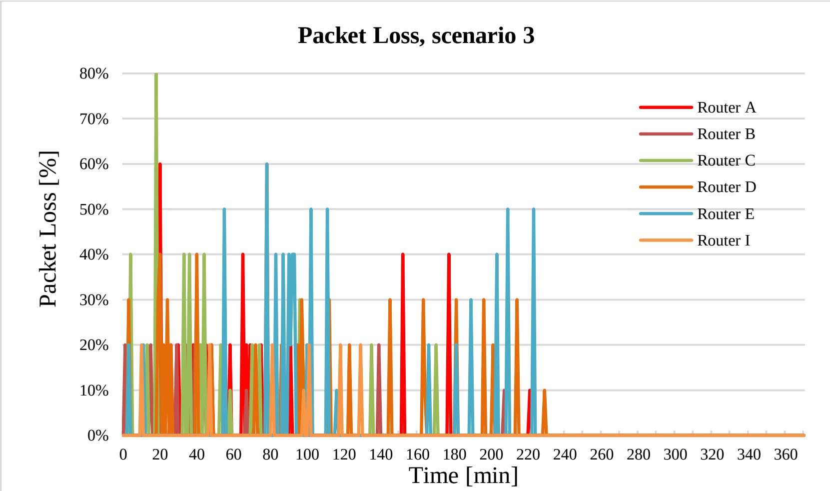

Figure 6.1 Packet Loss, scenario 3

Any protocol that changes routes quickly can become unstable. The instability arises because IP traffic can change dynamically. Two-stage oscillation effect can occur. In this case, the traffic switches between two paths back and forth. Such oscillations have undesirable consequences like inefficient bandwidth usage and frequent route computation. The benefit of DM-SPF is to quickly converge without the risk of oscillations because the idea is to achieve traffic load balancing.

6.2 Disadvantages

The method is an improvement but it is not a final solution to the traffic optimization problem. As is usually the case, the method has a possible cost. The traffic load caused by DM-SPF itself must be taken into consideration. The question is, how much bandwidth is used to send routing updates. It was found that the algorithm uses little bandwidth. Increasing number of transmitted control traffic causes short-term memory usage and CPU consumption due to the use of link state databases and the creation of the SPF tree.

A change in the topology is represented as a change in one or more of the LSPs. LSPs flooding process may degrade performance. The change causes new LSP flooding and new routing tables are computed. Regardless of how well the router can handle the packets, the packet's overhead will have some impact on performance. After the LSPs are flooded and stored in a database, each router is responsible for calculating the SPF tree for each known destination. On the other hand, LSP flooding is limited inside the affected area.

CONCLUSION

Being able to reliably communicate to anyone and anywhere plays an important role in our personal and business lives. In order to support immediate delivery of information being exchanged between people, users rely on effectively working interconnected networks. These networks are dependent on proper routing. Routing is a sophisticated network function that requires cooperation between routers and routing protocols.

The thesis offered the comparison of all routing protocols currently used in the Internet. There is a number of routing protocols from different manufacturers, but this thesis is focused on OSPF protocol, as it is commonly used. OSPF was discussed in depth. With gained pieces of knowledge it was revealed that there are still challenges to solve in OSPF routing process. The OSPF routing is limited by static metrics. OSPF may dynamically route around link failures but not around congestions.

A simple testbed was designed and created. This testbed represented a network testing environment that enabled to validate default OSPF routing behavior. From the results, it was obvious how OSPF drawbacks affected network performance. Default OSPF routing under high utilization caused packet loss, low throughput and no response to traffic congestion. Therefore, the main focus of this thesis was on a new method for better route selection while traffic load was also taken into account.

This thesis offered an approach of network congestion avoidance caused by individual links. The primary objective of the routing protocol was to determine the best paths for each route to include in the routing table. The routing algorithm generated a metric for each path through the network. This metric was based on two characteristics of a path - bandwidth and link load. It means that the novel method based route selection on multiple characteristics, combining them into a single metric. In general, the smaller the value of the metric led to the better path. The new method supported multipath routing. When there were multiple paths between DM-SPF routers, the paths shared the load.

When load became a variable used in determining a route and was used as a part of composite metric, DM-SPF was designed to avoid the impact of unexpected and accidental peak utilization. Such a burst of heavy traffic could destabilize the network. To ensure dynamic control of link load observations of routers, appropriate technique had to be applied. Exponentially Weighted Moving Average represented such tool for monitoring process variability. EWMA was more sensitive to small shifts in the process as compared to other techniques mentioned in the thesis.

The routing software was made as a process program providing all of the functionalities of a routing protocol. Not only when one of the links became utilized but also if there was a change in the topology, DM-SPF invoked the affected router to update the corresponding records in its database and warned the other nodes in that area. The goal was to split the traffic across multiple paths. To prevent frequent metric changes, load calculation was influenced by EWMA. The routers updated their link state databases, rerun the SPF algorithm, created a new SPF tree, and updated their routing tables. After a change, all routers had to agree on the network topology and achieve convergence.

The method was tested in a simulator and under real conditions. For the simulation of the method, Matlab was chosen as the most appropriate simulation tool since it offered flexibility and all the required functionalities. Performed simulations proved the proper function of the method and testing in the network under real conditions could follow.

There were three scenarios tested. These scenarios covered all possible situations that could occur. The results were discussed and described in graphs and tables. The advantages and disadvantages of DM-SPF were summarized in chapter 6. The method measurably increased the effectiveness and performance of the network in mentioned cases. This method not only made a best path determination but also a new best path when the initial path became unusable or if the topology changed. For these reasons, the method had an advantage over default OSPF routing protocol with its key feature - traffic awareness. DM-SPF made the most efficient use of the available bandwidth and distributed traffic across multiple paths.

As with every advance in communication technology, the creation of new methods had its drawbacks. Increased number of transmitted control traffic caused short-term memory usage and CPU consumption.

It was verified that DM-SPF met predefined goals. The proper functions and benefits were proved, examined and described. It was proved that the new method is able to support robust, reliable and efficient network.

Different people have different approaches to designing OSPF networks. The important thing to consider was that any protocol can fail under pressure. The idea was not to change the OSPF protocol but to adapt it in order to get the best performance.

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ABSTRACT

The massive growth of the Internet has led to increased requirements for reliable network infrastructure. The effectiveness of network communication depends on the ability of routers to determine the best path to send and forward packets to the desired destination. Open Shortest Path First (OSPF) protocol represents one of the most widely used routing protocols and its improvement to keep pace with the rapidly changing Internet environment would be greatly appreciated. The main deficiency of this protocol, among others mentioned in the thesis, is that its metric calculation algorithm does not take current link load into consideration. This is most likely to be the bottleneck in the path what has the most negative impact on network performance. To overcome the limitations of OSPF protocol and to improve the performance of routing in OSPF networks, a novel method based on dynamic adaptation to changing network conditions and alternative metric strategy is proposed. This method solves the problem of absence of traffic awareness and inconveniently congested links that decrease the network utilization. The method is also put into practice. The performance of new method is analyzed and verified by running the tests of the proposed algorithm on real network devices.