A delay-aware NUM-driven framework with terminal-based mobility support for heterogeneous wireless multi-hop networks

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***Abstract*—The idea of building a wireless mesh network, which aggregates the capacity from both user access lines and telecom providers links, is still far from reality, largely due to the lack of advanced resource management procedures and generalized node's mobility support. CARMNET - a Swiss-Polish project - aims at investigating delay-aware resource management for wireless multi-hop networks, providing also node mobility support. The project focuses on solutions that will motivate telecom providers to reconsider their view on user-operated wireless mesh networks. In this paper, we present the initial architecture design of a utility-oriented resource and mobility management framework that will be used in CARMNET-like networks. The framework is based on a delay-aware flow control mechanism and a solution for providing seamless Internet roaming.**

***Keywords*-wireless mesh networks; resource management; seamless mobility;**

I. Introduction

In the last few years, wireless mesh networking has been emerging as an important paradigm for enabling the communication of wireless devices located at short distances, and an alternative to the widespread 3G/4G Internet access. Very recently, this paradigm has been further extended by the idea of deploying multi-hop wireless networks operated jointly by telco operators and an informal community of Internet access-sharing users [1]. However, there are several scientific and technological challenges that need to be addressed to turn wireless mesh networks (WMNs) into a global network infrastructure [2]. Some works investigate solutions for ensuring satisfactory levels of reliability and sustainability of the user-provided Internet access sharing [1]. From the telecom operators perspective, there is lack of carrier-grade systems enabling them to measure the usage of shared Internet access, in particular systems providing users with appropriate incentives to share their Internet access with other users (possibly forming an informal community). Existing solutions for WMNs also suffer from reduced efficiency due to the lack of reliable self-configuration procedures, lack of efficient and scalable end-to-end QoS support, and lack of generalized and seamless mobility support. For example, there can exist different scenarios in which any node of a given network moves, and seamless connectivity must be provided to all the nodes of the network. The mobile network can change its point of attachment to the Internet, and the challenge would be to discover the mobility support capabilities of the access network and perform a handover from one network connection point to another, in an automatic and transparent way, ensuring the correct routing of packets, in order to provide users with the same perceived QoS. This problem is already hard for a single mobile node, and becomes even more difficult when it is a whole network that moves.

The CARMNET project [3] aims at achieving a significant experimentally evaluated improvement of the quality of heterogeneous 802.11 multi-hop network resource management and mobility support. This improvement will be experimentally evaluated in several testbeds, in particular in the research partner's testbeds being developed for the CARMNET research. The project will apply recent theoretical results in delay awareness of resource management, mobility management, and virtual per-utility charging, to WMNs in order to remove the issues that prevent WMNs to be attractive to telecom operators and to foster the adoption of existing wireless networking solutions. The project will use utility-oriented resource management for WMNs, in particular the one based on the Delay-Aware Network Utility Maximization (DANUM) framework [4], for network control. It will also use the Max-Weight Scheduling (MWS) [5] schema for performance optimization (throughput). In terms of mobility, CARMNET proposes a solution based on a cross-layer monitoring and control, and on the adaptation and the integration of the WiOptiMo [6] platform with the DANUM subsystem. WiOptiMo provides seamless inter-network roaming by handling mobility at the application layer. The main advantages of using it for a mobile network are seamless network mobility support across wired and wireless access networks, scalability, QoS support and compatibility with the most popular mobile devices.

In this paper we present the initial system design of a utility-aware optimization framework for wireless multi-hop networks, with mobility support. We start from presenting the basic principle of the WiOptiMo framework, then we describe the architecture of a typical CARMNET network implementation and the WiOptiMo configuration for a CARMNET network. Section IV-A and IV-B describe the network monitoring solution of the DANUM CARMNET subsystem and the CARMNET mobility subsystem. Finally, in Section IV-D we show how the two modules were integrated to provide an efficient delay-aware NUM framework with mobility support for WMNs.

II. Related work

Network mobility support is addressed in RFC 4886, written by the IETF NEMO Work Group [7]. Network Mobility Support is defined as "a mechanism that maintains session continuity between mobile network nodes and their correspondents upon a mobile router's change of point of attachment". It is provided by means of a bidirectional tunnelling solution [8], much like what is done with Mobile IPv6 [9], which is a network layer protocol for managing mobility in an IP network. Mobile IP based solutions suffer from performance degradation due to encapsulation and the lack of QoS capabilities, so they are not well suited for supporting multimedia services with QoS requirements (*e.g.*, VoIP, VoD, IVVR).
A scheme based on cross-layer monitoring of the communication status is a better approach to select a new point of attachment to the network. For this reason, we propose to use WiOptiMo for network mobility management in a wireless multi-hop CARMNET network. WiOptiMo effectiveness for supporting seamless mobility of a whole network was already described in [10]. In Section II-A, we describe WiOptiMo's architecture and its characteristics. For the sake of clarity, we focus on the special case of a client-server architecture. In Section IV-B, we present a modified version of WiOptiMo, designed for providing QoS mobility support to different application flows in a CARMNET network.

A. WiOptiMo Description

WiOptiMo is an application layer solution for seamless mobility. It has been fully described in [6]. Here, we recall its main characteristics.
WiOptiMo enables a handover initiated by the mobile device, detects the points of attachment to the network and automatically provides the best Internet connection in terms of QoS. Mobility management and seamless handover are handled by two main components: the Client Network Address and Port Translator (CNAPT) and the Server Network Address and Port Translator (SNAPT). These two components form an interface between a client application and the server and give them the illusion that there is no mobility in the system. The CNAPT and the SNAPT collectively act as a middleware (Figure 1) so that the client believes to be running either on the same machine as the server or on a machine with a stable direct connection to the server (depending on the configuration adopted). The CNAPT is an application that can be installed on the same device as the client application or on a different device in the same mobile network. Similarly, the SNAPT is an application that can be installed on the same device as the server application, on a different device of the same network, or on any Internet server (*e.g.*, on a corporate front-end server, on a home PC connected to Internet, on a mesh router, or on an 802.11 access point). This flexibility of the SNAPT installation is particularly important because it avoids scalability issues and allows to manage mobility either using a star topology with a central server with large computational capabilities and large bandwidth, or with a distributed topology where the SNAPT is installed on the accessible nodes (i.e., mesh routers), saving transmission costs and/or minimizing network metrics (*e.g.*, delay, etc.).
During normal communication, the CNAPT relays the client requests to the SNAPT that manages the server. Upon receiving client requests, the SNAPT processes them and in turn relays them to the corresponding servers. The server response path mirrors the client request path.
During a handover phase, the CNAPT and the SNAPT enable a transparent switch to the new selected connection. The applications data flow is interrupted at the CNAPT, which stops forwarding the outgoing IP packets generated by the client. The SNAPT also stops forwarding all the outgoing packets generated by the server. The packets already stored in the transmission buffers of both the CNAPT and the SNAPT sockets will be forwarded, respectively, to the SNAPT and the CNAPT after the completion of the handover.

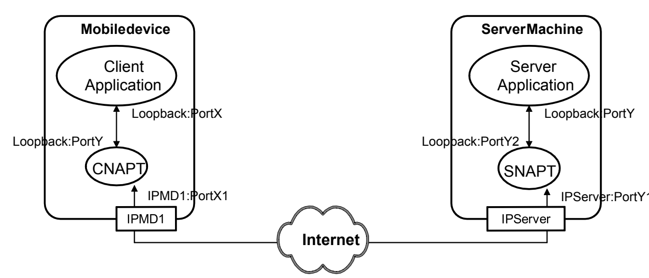

Figure 1. The CNAPT and the SNAPT collectively act as a middleware.

III. CARMNET architecture and WiOptiMo

A CARMNET network, *i.e.* a wireless network that allows its end-user to share their network resources, is defined on the basis of two scenarios representing different types of connections (one-hop versus multi-hop) available in

the network: fully-connected and multi-hop mesh scenario. For the sake of simplicity, we consider a fully connected mesh scenario, but the extension to a multi-hop scenario is straightforward.
The basic architecture of a wireless fully connected CARMNET network consists of the following type of devices (Figure 2):

- CARMNET wireless mobile network nodes;
- CARMNET Internet-sharing nodes;
- an Open SIP-based IMS Core system, which allows delivering of IP multimedia services.

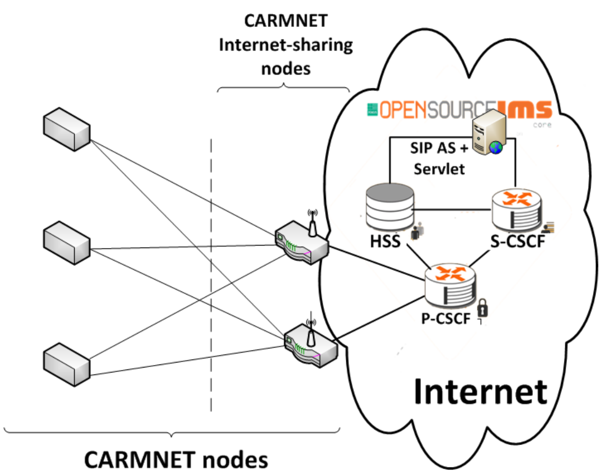

Figure 2. Fully-connected mesh CARMNET scenario.

A. WiOptiMo configuration for a CARMNET network

Figure 3 shows WiOptiMo's configuration for a CARMNET network.
A CNAPT is located on each mobile wireless node. This design provides mobility services to any user's device in the network, without depending on the availability of a service in a neighbour node. It also allows the user's device to roam freely inside the network and select any Internet sharing node, as a consequence of either a charging policy or a network topology change, without disrupting a service.
To avoid overusing the mobility services, a charging scheme dependent on services' bandwidth and latency requirements, and on the available resources, will be defined. In this way, most of the user's devices will use mobility support only when network service continuity is really needed (such as VoIP or an interactive shell).
To complement the DANUM-based approach taken by CARMNET, which controls flows' utility at application layer, the CNAPT at a source node will mark the traffic flows established using mobility services, identifying their requirements in terms of bandwidth, delay, etc.
To provide a scalable mobility service, multiple SNAPTs will be placed in the Internet to avoid concentrating traffic flows in a single spot. The SNAPT where to relay the traffic, will be chosen by the CNAPT, based on both network status and a user configurable policy.
The proposed architecture has both advantages and disadvantages. The presence of the CNAPT on any mobile node provides complete flexibility over the choice of the Internet sharing node (because it could be changed at any time without service interruptions), generating competition. Moreover, the presence of multiple SNAPTs will allow user's device to choose between multiple mobility providers, keeping the prices down and/or pushing the provider to increase the quality of the service. However, this comes at the cost of a slightly more complex architecture at the mobile node, since one additional component (the CNAPT, in addition to the DANUM subsystem) has to be hosted.

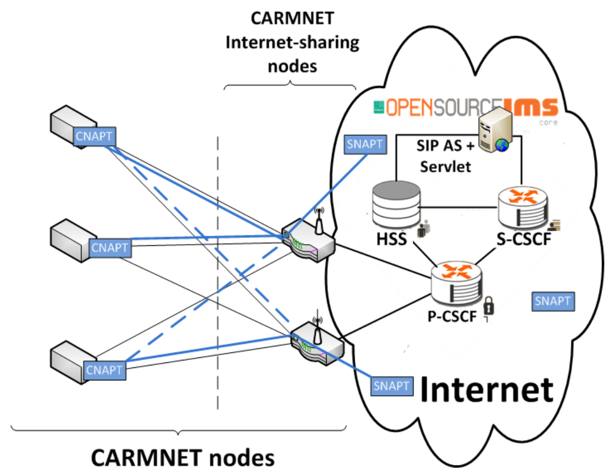

Figure 3. WiOptiMo configuration for a fully-connected mesh CARMNET scenario.

IV. Utility-aware optimization framework with mobility support

In this section we show how the network monitoring functions imposed by the DANUM framework and the network metrics used by WiOptiMo can be combined to provide the utility-aware optimization framework with mobility support for wireless multi-hop networks proposed in this paper.

A. End-to-end delay and throughput monitoring provided by DANUM LKM

The CARMNET wireless multi-hop network uses the Delay-Aware NUM (DANUM) framework for flow control and packet forwarding of multi-class traffic. The main futures of the DANUM system architecture are:

- It is based on the application of an optimization variable that can be defined as the 'price of meeting the service quality requirements and the definition of a "virtual money" called *denarii* associated with the optimization variable.

- The decomposition into two architectural elements: one aimed at indirect sender-side flow control based on the denarii rate control, and one representing the packet forwarding component, aimed at providing the approximation of backpressure Max-Weight Scheduling.
- It is integrated with dynamic (fully proactive) routing based on a multi-path extension of the OLSR protocol to allow the backpressure-based packet forwarding optimization [11].

The indirect sender-side flow control requires a real-time monitoring of flows' utilities (transmission quality) based on the measurement of end-to-end throughput and end-to-end delay. The flow-centric monitoring solution is based on the exchange of DRP (Delay Reporting Protocol) messages, which are sent periodically, in parallel with regular data packets. A DRM message (Figure 4) is composed of a message header and Delay Information Blocks (DIBs) as shown in Figure 5. The header contains a unique flow identifier (source and destination addresses followed by port numbers), a timestamp for the dispatching time and a flag to specify the direction of message propagation [4]. Each DIB block contains the identifier of a link and message arrival timestamps (FDAT, RDAT).

0 7 15 23 31

Next-hop		
Source Address		
Destination Address		
Source Port		Destination Port
Timestamp		
D	Reserved	Rate
DIB (16B)		
. . .		

Figure 4. Delay Report Message (DRM).

0 7 15 23 31

Sender Address
Receiver Address
FDAT
RDAT

Figure 5. Delay Information Block (DIB).

Figure 6 shows how DRP messages are transmitted between a source and a destination node to calculate the end-to-end delay, which is based on the timestamps difference. The experienced end-to-end throughput is calculated at the flow destination node according to the amount of received data monitored in constant periods of time. The additional mechanism of DIB blocks enables [4]:

- to use the same route when DRM returns to the flow's source node (see Figure 6);
- to support the routes calculation algorithm with preventing forming of a loop, by gathering path history within DIB blocks;
- to provide further optimization leading to more advanced multi-path delay reporting.

B. Mobility monitoring solution

Considering that each CNAPT and SNAPT can handle multiple flows, the possibility to physically distribute CNAPT and SNAPT components in the network, can really allow for significant performance optimization.
Within the scope of the EU-MESH project [12], we introduced the Controller component, for the selection of the appropriate SNAPT at run-time. The Controller is contacted by a CNAPT at start-up to get the SNAPT's address. During a handover, the Controller notifies the CNAPT whether a "better" SNAPT is available, and the CNAPT possibly connects to the new SNAPT. The metric to quantify the quality of a SNAPT is a function of metrics referred to the network where a SNAPT is running (*e.g.*, available bandwidth, network latency, packet loss). In order to achieve more flexibility and better performances, in CARMNET we concentrate on parameters of the application flows that are transmitted through the Internet. The task to choose the proper SNAPT is assigned to the CNAPT. The list of SNAPTs is statically set at a CNAPT (*e.g.*, via a configuration file) and is automatically updated via messages sent by the connected SNAPT. A CNAPT selects the SNAPT at start-up and/or at run-time, during a handover. The metric used for the selection is a function of:

- *End-to-end throughput*. A CNAPT periodically evaluates the network (TCP/UDP) throughput of its flows towards the SNAPT: if the current SNAPT is overloaded, a SNAPT with a smaller network load is selected. The throughput is calculated by a SNAPT based on the amount of received data monitored over a time period.
- *End-to-end delay*. Since in CARMNET we mainly deal with streaming data, we take into account the one-trip time (OTT), as it determines the level of utility perceived by a user. Only a SNAPT which ensures the QoS requirements of the running applications in terms of delay, is selected.

As described in Section III-A, a key point for the mobility monitoring system is traffic flow classification. The classical approach to traffic classification relies on mapping applications to well-known port numbers. To avoid detection by this method, P2P applications began using dynamic port numbers, masquerading techniques, and encryption. Many recent studies confirmed that port-based identification of

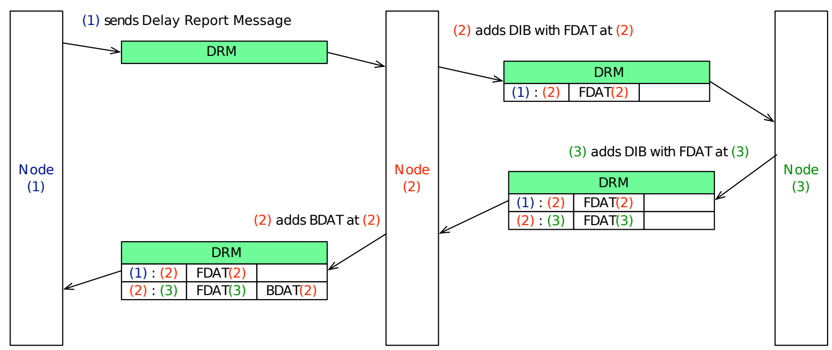

Figure 6. MSC-like diagram presenting the DRM mechanism.

network traffic is ineffective [13]. For the above reasons, we propose to use a header-based approach for classifying application flows. One key element is the transport protocol (TCP, UDP, or other), which indicates whether the traffic under test tolerates unreliable delivery. However, there are well known applications that use an unreliable protocol even if unreliable delivery may cause a significant drop in the QoE level. DNS is a case in point: a dropped name lookup packet may cause an extended delay for the application (compensated by protocol-level caching). Another key element is the packet length, which correlates well with the delay-tolerance of the application data. For instance, a transmission flow composed by small packets is certainly delay sensitive, while a flow whose packets typically match the Maximum Transmission Unit (MTU) size contains delay tolerant data because the generating application can wait for the whole data before starting transmission.
These heuristics can be improved when the CNAPT is running on the same machine as the generating process. In this scenario, it is possible to apply a predefined per-application policy: if an application is unknown, it is still possible to refine the previous techniques by keeping long term per-application statistics.

C. Subsystems cooperation

Figure 7 shows the areas in which network measurements are performed by both the DANUM and WiOptiMo solutions. The DANUM subsystem works inside the CARMNET network, being deployed on each node. This solution allows to get accurate measurements of each flow's parameters inside the local network. The mobility subsystem is designed to provide measurements of delay over the Internet. However, the measurement corresponds only to the delay on the particular route that flow traverses, which is not necessarily equal to the delay experienced by flow. Nevertheless, the provided delay is a good enough estimation.

1) CNAPT-SNAPT measurements as mean of extending capabilities of the DANUM subsystem: The information about delay experienced by flow is essential for the utility calculation. As discussed in Section IV-A, the current monitoring of the DANUM subsystem provides the highly accurate measurement. However, in a scenario where a node from an external network is involved, the DRP mechanism fails. In that case, since all the external traffic is served by the mobility subsystem, the DANUM subsystem can combine data shared by the CNAPT with its own monitoring data to get an extended estimate of end-to-end measurements.

2) Pro-active CNAPT-SNAPT measurements as route metrics: The selection of the best SNAPT is done by pro-actively measuring network metrics on the border CARMNET nodes (Internet-sharing). Information about the end-to-end delay between the CNAPT and the SNAPT is transformed into a metric of particular route to the SNAPT host node. The route, along with metric information, is broadcast in the extended HNA OLSR message [11]. This solution allows other CNAPTs (hosted on non-border CARMNET nodes) to select the best routes (by selecting the border node) to the SNAPTs.

D. DANUM and mobility subsystems cooperation

The DANUM module is implemented as a loadable Linux Kernel Module (LKM). The communication with external processes takes place by presenting data as a regular file, and was achieved by implementing the *procfs* interface [14]. The procfs mechanism can be used both for exporting flow properties from the DANUM subsystem and for providing additional measurement information from external source to the DANUM subsystem.
A file exported from DANUM can be read by any application both in the user-space and the kernel-space. Figure 8 shows the format of the file. Each line of the file consists of distinct fields separated by single white-spaces. The first line contains the name of each column:

- *no*: entry number;
- *src_address*: source address, consisting of IP and port number in hexadecimal format, separated by a single colon;

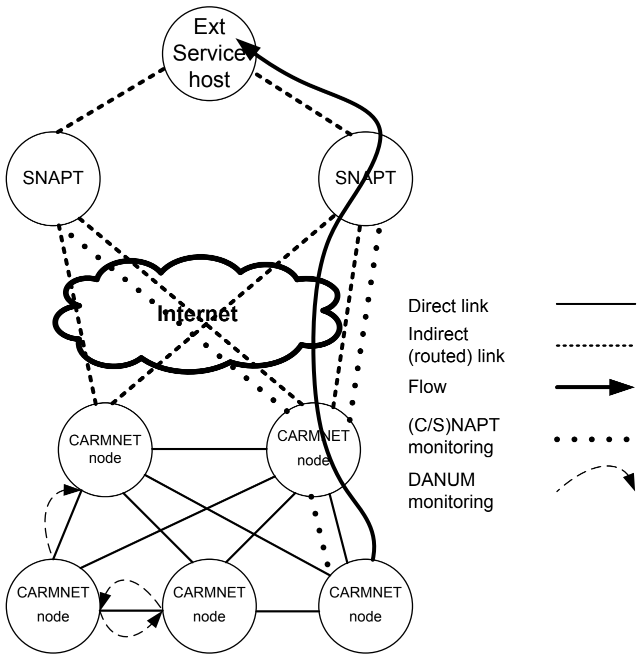

Figure 7. Areas covered by monitoring solutions.

- *dst_address*: destination address (same format as *src_address*);
- *protocol*: protocol number in hexadecimal format;
- *delay*: estimated OTT delay in ms;
- *throughput*: flow throughput in bytes per second.

The procfs mechanism is also used to provide additional information directly to the DANUM LKM. Since supplied information could be incomplete, an asterisk is used when particular information is missing. For example, if there is information about the delay on a route between two hosts, but this does not represent the delay for a particular flow, the ports and protocol numbers should be replaced by asterisks.

no	src_address	dst_address	protocol	delay	throughput	price
1	9C29FE96:E624	BD4EC2AD:0102	06	120	2402	1234
2	9C29FE96:C3E6	BD4EC2AD:01BB	06	156	4566	100
3	9C29FE96:8C9B	1346C2AD:01BB	11	30	134	4500

Figure 8. File $/proc/net/danum\_flows$ content example.

V. Conclusion

We presented the design architecture of a framework for utility-oriented resource management with mobility support, in a wireless multi-hop mesh network. The framework is based on the integration of a delay-aware flow control algorithm with a packet forwarding component aimed at providing an approximation of Max-Weight Scheduling, and an empirical solution providing seamless Internet roaming to the whole wireless mobile network. A research implementation of this solution is being in progress within the scope of the CARMNET project. Future experiments conducted in a mobility-oriented scenario of infotainment and conversational services, will evaluate the effectiveness of the network resource and mobility management mechanisms.

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References

[1] C. Middleton and A. Potter, "Is it good to share? a case study of fon and meraki approaches to broadband provision," in *Proceedings of International Telecommunications Society*, Montreal, 2008.

[2] G. V. A. Balachandran and P. Bahl, "Wireless hotspots: Current challenges and future directions," in *Proceedings of WMASH'03*, San Diego, California, 2003, pp. 265–274.

[3] [Online]. Available: http://carmnet.eu

[4] A. Szwabe, P. Misiorek, and P. Walkowiak, "Delay-aware num system for wireless multi-hop networks," in *Proceedings of European Wireless 2011*, Vienna, Austria, 2011, pp. 530–537.

[5] L. Tassiulas and A. Ephremides, "Stability properties of constrained queueing systems and scheduling policies for maximum throughput in multihop radio networks," in *IEEE Transactions on Automatic Control*, 1992, pp. 1936–1948.

[6] G. A. D. Caro, S. Giordano, M. Kulig, D. Lenzarini, A. Puiatti, F. Schwitter, and S. Vanini, "Wioptimo: A cross-layering and autonomic approach to optimized internetwork roaming," in *AHSWN Journal*, May 2007, pp. 104–113.

[7] T. Ernst and L. H., "Network mobility support terminology," RFC 4885, July 2007.

[8] V. Devarapalli, R. Wakikawa, A. Petrescu, and P. Thubert, "Network mobility (nemo) basic support protocol," RFC 3963, January 2005.

[9] D. Johnson, C. Perkins, and J. Arkko, "Mobility support in ipv6," RFC 3775, June 2004.

[10] S. Giordano, M. Kulig, D. Lenzarini, H. Nguyen, A. Puiatti, and S. Vanini, "Demonstrating seamless handover of multi-hop networks," in *Proceedings of REALMAN '06*, Florence, Italy, May 2006, pp. 128–130.

[11] A. Szwabe and P. Misiorek, "Integration of multi-path optimized link state protocol with max-weight scheduling," in *Proceedings of ICIMT 2009*, Jeju Island, South Korea, 2009, pp. 458–462.

[12] Eu-mesh. [Online]. Available: http://www.eu-mesh.eu

[13] T. Karagiannis, K. Papagiannaki, and M. Faloutsos, "Blinc: Multilevel traffic classification in the dark," in *SIGCOMM'05*, Philadelphia, USA, pp. 229–240.

[14] Proc - linux man page. [Online]. Available: http://linux.die.net/man/5/proc