# Cooperative Internet Access Sharing in Wireless Mesh Networks

Vision, Implementation, and Experimentation of the CARMNET Project

Mariusz Glabowski, Andrzej Szwabe
Poznan University of Technology
Poznan, Poland
e-mail: mariusz.glabowski@put.poznan.pl,
andrzej.szwabe@put.poznan.pl

Dario Gallucci, Salvatore Vanini, Silvia Giordano
Institute for Information Systems and Networking
University of Applied Sciences and Arts of Southern Switzerland, Manno, Switzerland
e-mail: dario.galluci@supsi.ch, salvatore.vanini@supsi.ch,
silvia.giordano@supsi.ch

*Abstract*— **The paper presents the vision, as well as the main results of the implementation and the experimentation performed within CARMNET – a Swiss-Polish project aimed at investigating "CARrier-grade delay-aware resource management for wireless multi-hop/Mesh NETworks". The project focuses on solutions that motivate telecom operators to reconsider their view on user-operated IEEE 802.11-compliant wireless mesh networks. It is driven by the vision of networks operated cooperatively by telecom operators and a community of users. While the former may appreciate the CARMNET's compliance with IP Multimedia Subsystem (IMS) infrastructure, the latter likely enjoy the pervasiveness of the CARMNET-based Internet access. The project aims at providing, both telecom operators and end users, with solutions that will create appropriately strong incentives – technological, functional and economical – for a widespread adoption of CARMNET-like networks within an expanding group of users. Project results obtained so far indicate, that despite the originality of the project vision, its solutions are applicable to the telecom operator's infrastructure, in particular in Internet access sharing scenarios that become widespread in the recent years.**

***Keywords – wireless mesh networks; wireless mesh testbeds; user-operated Internet access sharing; IMS; mobility.***

## I. INTRODUCTION

The core idea of the CARMNET project [1], [2] is to make the user-provided Internet access an important alternative to the currently widespread 3G/4G-based mobile Internet access, in particular this provided in the femtocell scenario [3]. The main assumption of the project is that wireless mesh networks [4], while effectively enhanced by the introduction of advanced resource management mechanisms [5] and the compliance with the core of the telecom operators' IMS-based Authentication, Authorization, Accounting (AAA) infrastructure [6], [7], may serve as an appropriate basis for a real-world realization of the core CARMNET idea.

However, the realization of the vision of CARMNET networks – as operated jointly by telecom operators and an informal community of Internet access-sharing users – has raised several scientific and technological challenges that had not yet been investigated in a satisfactory detailed way [8], [9]. The scenario-driven research efforts of CARMNET have resulted in a set of solutions for ensuring satisfactory levels of reliability and sustainability of the user-provided Internet access sharing. The completed and the ongoing research is focused on algorithms for reliable servicing of multi-service traffic, with different packet delay tolerance, including algorithms related to: traffic stream classification, packet scheduling, buffer memory management, routing and nodes mobility management [10], [11].

Targeting the CARMNET objectives has implied the need for addressing several technological challenges, in particular those related to the compatibility with the key relevant standards, such as Optimized Link State Routing (OLSR) protocol for the reliable multi-criteria routing within wireless mesh networks [12], [13], [14], or relevant to IMS-based AAA [15] technologies used by telecom operators [16]. Moreover, as far as the long-term sustainability of CARMNET is concerned, some user-centric features have proved to be of the key importance, as well. They correspond to functional aspects of a CARMNET network use, such as the user-perceived network utility and the user-friendliness of mobile applications running on smartphones that constitute such a network.

The further part of the paper is organized as follows. In Section II, the CARMNET research motivation is presented. Section III describes the central role that scenarios play in the project. In Section IV, selected technological solutions developed for CARMNET-like networks are presented. Section V presents the multi-testbed experimentation approach for evaluating project's outcomes. The summary of the key practical results of the CARMNET research and the presentation of the conclusions close the article.

## II. RESEARCH MOTIVATION

Internet access sharing via customers' WiFi access points is a service recently deployed by several world's leading telecom operators, including Orange and British Telecom (BT). For example, in Poland such a service is offered by Orange as FunSpot [17]. The service known as FON [18] is offered in several countries by partners of BT, e.g., by Polish operator Netia [19].

However, the attractiveness of wireless mesh networks to telecom operators, despite a significant research effort that has been put in the last decade [8], remains quite limited. The following issues related to the CARMNET vision may be recognized as potentially postponing the wide adoption of existing wireless networking solutions:

- The lack of integration between the wireless network resource management and the AAA mechanism of telecom operators IMS-compliant networks,
- The lack of carrier-grade systems enabling telecom operators to measure the usage of shared Internet access in wireless mesh networks,
- The lack of solutions enabling end users to request the same level of Quality of Service (QoS) parameters as in 3G/4G networks,
- The lack of integration of the wireless network resource management oriented on the Network Utility Maximization (NUM) with 'utility-aware' accounting, in particular in a scenario in which users are provided with 'society-building' incentives similar to those familiar to users of popular Internet file-sharing applications based on the Peer-to-Peer (P2P) protocols [20],
- The lack of seamless mobility support for multimedia services with QoS requirements [11].

It is worth mentioning that the scope of CARMNET research corresponds to the recent trend of intensive studies on various wireless Internet access sharing methods [21]. Moreover, similar scientific projects have been recently conducted, including EU CARMEN [9]. However, to the best of our knowledge, all such initiatives differ from CARMNET in one of its core assumptions: they are based on the use of non-standard hardware and they are dependent on the access technologies.

## III. CARMNET SCENARIOS

The CARMNET research methodology follows the approach of the user-centered scenario-based design, focused on functional specification of the system in correspondence to the user requirements and activities [22]. Firstly, descriptions of CARMNET application scenarios constitute the core of the project vision by focusing on the user-centric view on added-value functionalities and the user-perceived incentives for cooperative use of CARMNET-based networks – both potentially enabled by the use of CARMNET technological solutions. Secondly, the CARMNET network topology scenarios [1] have served as the basis for a more detailed specification of CARMNET research scope, and serve as a starting point for network topology definitions followed in multi-testbed experimentation-oriented activities [23].

There are two main CARMNET Application Scenarios. The first one assumes the cooperative Internet access sharing as being realized via CARMNET access points, while the second one assumes the use of CARMNET mobile nodes for the same purpose. Each of the scenarios includes the 'phase' of earning virtual currency units (called denarii) by a user sharing his/her home network resources and the 'phase' of

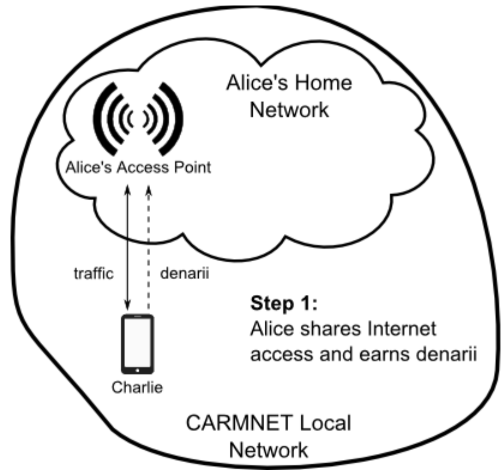


Figure 1. The first step of the first CARMNET Application Scenario: Alice 'earns' denarii by sharing her home network with Charlie.

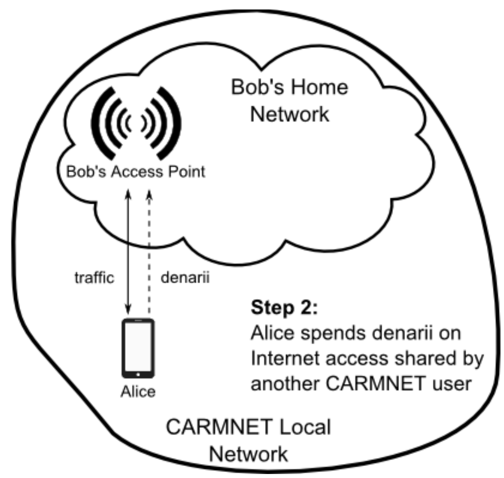


Figure 2. The second step of the first CARMNET Application Scenario: Alice 'spends' her denarii by using Bob's home network.

spending denarii for using the resources of a visited network. An example in which Alice earns denarii by sharing her home network with Charlie (Scenario 1) and then spends her denarii by using Bob's home network (Scenario 2) is depicted in Figure 1 and Figure 2, respectively.

It may be noticed that the CARMNET Scenario 1 is architecturally similar to scenarios of currently offered services, as it is based on the assumption that the core functions of Internet access sharing are realized by means of WiFi access points (appropriately equipped and configured), i.e., the WiFi access point is the border node of the network with shared resources. However, CARMNET provides a utility-based charging based on the application of virtual units of utility (called denarii) as added value [5], [7].

In both the basic CARMNET scenarios, the scope of the 'utility-sensitive' traffic management [5], [24], which is realized in the home user's WiFi network, is naturally limited to the WiFi network's range. However, in the case of CARMNET Scenario 2, illustrated in Figure 3 and Figure 4, the scope of the Internet access sharing may be extended by means of CARMNET traffic-relaying mobile nodes. As a

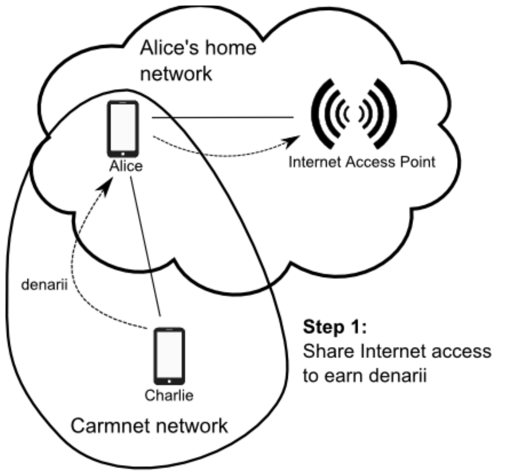


Figure 3. The first step of the second CARMNET Application Scenario: Alice 'earns' denarii by sharing her mobile Internet access with Charlie.

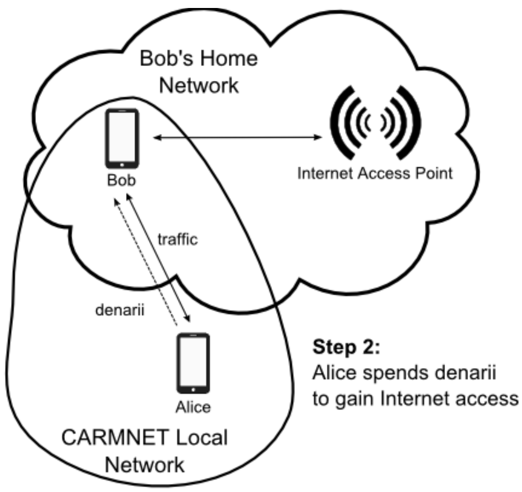


Figure 4. The second step of the second CARMNET Application Scenario: Alice 'spends' her denarii by using Bob's mobile Internet access.

result, the network coverage may be widened without additional investments on the telecom operator's side [7].

CARMNET supports both the WiFi-mobile and the WiFi-WiFi traffic relaying modes. However, as WiFi connectivity is much more power-consuming than a mobile Internet access (3G or 4G access provided by a telecom operator), the real-world applicability of the CARMNET multi-hop WiFi-to-WiFi traffic relaying - as shown in Figure 5 presenting the CARMNET multi-hop application scenario - is practically limited to cases in which the user has an easy access to a power supply, e.g., when he/she shares his/her mobile Internet access with drivers of other cars staying in the same traffic jam area.

Currently, a typical multi-hop WiFi-to-WiFi traffic relaying scenario can be used by mobile operators in order to extend the range of their networks. However, one of the key problems in multi-hop wireless networks, especially in networks that serve heterogeneous traffic, is optimal resource management and routing. In order to make multi-hop networks attractive for telecom operators, within the CARMNET project the development of a resource management system and a multi-criteria routing were undertaken.

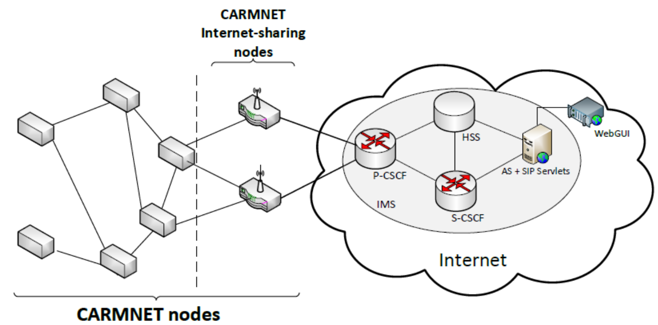


Figure 5. CARMNET multi-hop application scenario.

## IV. Key Areas of CARMNET Research

The implementation of the CARMNET vision required integrated studies in several research areas that are usually investigated independently, such as multi-criteria routing, wireless network resource management and integration of a NUM system with IMS core infrastructure aimed at providing SIP-Based AAA Support [6].

### A. *Multi-Criteria Routing*

Within the activities related to CARMNET project, a new routing protocol (based on the OLSR protocol), which allows for multi-criteria path selection, is proposed. The protocol is capable to build the routing table (at each node), including not only the best path but a set of paths that lead to the specified destination network. The paths in the set are selected as the subsequent shortest paths to the specified destination, based on one of the *k*-shortest paths algorithms [25], [26], [27]. The paths are determined according to main criterion, e.g., delay, and they include additional criteria (metrics). The additional metrics are useful in order to choose the best path that fulfils the criteria for a given traffic stream. The criteria correspond to the QoS requirements for all traffic classes offered in the CARMNET network. An example of the criteria can be delay, a number of hops, link reliability or link load.  Thus, the proposed QoS routing protocol is able to use different traffic profiles and for each of them proposes the best path, i.e., the path that fulfils recommended (for the considered traffic profile) QoS values in the best possible way.

The multi-criteria routing is dedicated primarily to the multi-hop scenario, but it can be also used in the single-hop scenario, to select the best CARMNET Internet-sharing node. Additionally, the routing protocol introduced in the CARMNET system may be also used as one of the possible methods for mobility management: one or more of the criteria can be used by a mobile node to select the best path (next-hop node) for a traffic stream of a given class.

### B. *Wireless Network Resource Management based on Delay-Aware Network Utility Maximization (DANUM) Approach*

The aim of the DANUM model is to provide an optimal packet scheduling policy regarding the maximisation of the network users' satisfaction. It targets the maximum of the network utility (a sum of utility of all flows within the network):

$$\max \sum_{r \in S} U_r(x_r, d_r), \qquad (1)$$

where $S$ denotes a set of flows within the network; $x_r$ – rate of flow $r$; $d_r$ – delay of flow $r$; $U_r$ – the utility function of flow $r$. In other words, DANUMS aims at solving the NUM problem in a delay-aware way. The relation between measurable flow transmission quality parameters and its utility is modelled by means of a utility function. Each function corresponds to flows of a given type or, more precisely, to flows with specific network requirements [5].

In DANUMS the utility is determined not only according to the flow's throughput, but also to its end-to-end delay. Each flow may have a distinct utility function since it may prioritise different network performance parameters. Assigning utility functions to flows is a task of the Flow Classifier [10].

It has been proven that the Max-Weight Scheduling (MWS) algorithm is a solution to the standard throughput-oriented NUM problem formulation [28]. The DANUMS applies the MWS algorithm to virtual queue levels in order to determine the next flow queue to transmit a packet from. A virtual queue is defined as a product of flow's packet backlog level and a virtual price of a single packet. Packet's virtual price is a value of the derivative of a utility function assigned to the flow. In other words, the more utility a flow would gain from improving its network performance parameters (e.g., by lowering its delay), the higher is the virtual price. The virtual price plays an important role in packet scheduling as well as influences the cost of CARMNET network usage [10].

### C. *Wireless Network Resource Management Based on Multiservice State-Dependent Queueing Models*

Another key objective of the CARMNET project in the area of resource management is to elaborate a model of a multiservice queuing system. A careful review of the available literature reveals that no satisfactory models of multiservice queueing systems have been developed as yet. The proposed solutions [29], [30], [31], [32] concern a certain number of boundary cases only and do not provide methods for individual evaluation of queue parameters for individual classes of calls. The advantage of the proposed in CARMNET project model will be opportunities to evaluate analytically the average parameters of queues for individual classes of calls, which may prove to be of particular importance in engineering applications, especially in solutions concerning the analysis, dimensioning and optimization of mobile networks.

Within the CARMNET project, an accurate model of a state-dependent queuing system with limited queue and state-dependent dynamic resource sharing between individual classes of streams was proposed. The assumption was that the queueing system had a server with the capacity $C$ and the queue with the capacity $U$, expressed in AUs (Allocation Unit) [33], [34]. The assumption in the model was that the allocation unit had the value 1 bit/s, (or 1 Kbit/s, 1 Mbit/s and so on, depending on the adopted bit rate units appropriate for a considered system). In the proposed queueing system, the number of AUs that service streams of class $i$ ($1 \leq i \leq M$, where $M$ is the number of classes of offered streams) in the server depends on the number of streams of individual classes in the system at a given moment of the service process. This defined system can be also treated as $M$ virtual queueing systems in which bit rates, allocated in the server to service streams of particular classes, depend on the number of currently serviced streams and streams placed in $M$ queues (see Figure 6).

Figure 6 shows a diagram of a queueing system to which two classes of traffic streams are offered. The figure shows two virtual queues, though, in real circumstances, there is only one queue for all classes of streams. This particular presentation of the system results from the fact that the resources allocated in the server to service particular classes depend on the total number of streams in the system, while they are independent of the actual order of call arrival to the system [33], [34].

It is proved in [34] that the distribution of the number of streams $[p(X)]_{C+U}$ currently in thus defined queueing system (being serviced in the server and waiting in the queue) can be written as follows:

$$[p(X)]_{C-U} = \begin{cases} \frac{1}{n_X} \sum_{i=1}^{M} A_i [p(X - 1_i)]_{C+U} & \text{for} \quad X : 0 \leq n = \sum_{i=1}^{M} x_i(X) c_i < C, \\ \frac{1}{C} \sum_{i=1}^{M} A_i [p(X - 1_i)]_{C+U} & \text{for} \quad X : C \leq n = \sum_{i=1}^{M} x_i(X) c_i < C + U, \end{cases} \qquad (2)$$

where $X$ is the state of the service process defined by the number of streams $x_i(X)$ of particular classes currently being in the system: $X = \{x_1(X), x_2(X), \ldots, x_M(X)\}$, $A_i$ is the traffic intensity of class $i$, defined relative to AU [33], [34], $c_i$ is the bit rate of a stream of class $i$, the $n_X$ parameter denotes the total number of allocation units in the system in state $X$, whereas $1_i$ denotes one stream of class $i$.

On the basis of (2) it is possible to determine all important averaged characteristics for streams of individual classes, e.g., the average value $Q_i$ of the number of streams

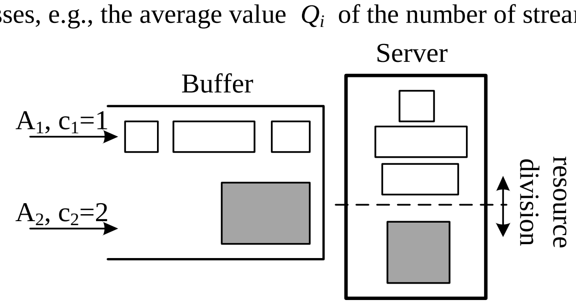


Figure 6. Multiservice queueing system with state-dependent dynamic distribution of server resources.

of class *i* waiting in the queue can be expressed by the following formula:

$$Q_i = \sum_{\Omega} \left[ x_i(X)[p(X)]_{C+U} - \frac{A_i}{c_i}[p(X-1_i)]_{C+U} \right], \quad (3)$$

where Ω is the set of all states in which the queue is not empty:

$$\Omega = \left\{ X : C \le \sum_{i=1}^{M} x_i(X)c_i \le C+U \right\}. \quad (4)$$

The proposed model of the state-dependent queuing system with limited queue and state-dependent dynamic resource sharing between individual classes of streams is the first accurate multiservice queueing model that makes it possible to evaluate queues for individual classes of calls. Within this context, the opportunities offered by its practical applicability exceed the scope of the CARMNET project. The model can be particularly important in engineering applications, particularly those that are related to the analysis of 4G mobile networks and other telecommunications systems that use buffers.

### D. *Integration of Wireless Network Resource Management with Routing and AAA Functions*

One of the key objectives of CARMNET is to integrate IMS-based AAA support with the utility-oriented resource management for wireless mesh networks, in particular the one based on DANUM System (DANUMS) [6], [7]. DANUMS is an application-layer system providing a delay-aware indirect flow control mechanism based on a system transporting virtual utility units and a packet forwarding component aimed at providing an approximation of Max-Weight Scheduling (MWS) [24].

The DANUMS is a part of an architecture (see Figure 7) that consists of a routing component in the form of Optimised Link State Routing Protocol daemon (OLSRd) [12], a custom SIP User Agent integrated with a Linux Loadable Kernel Module (LKM), a user interface (WebUI) and an IP Multimedia Subsystem (IMS) platform [16]. SIP User Agent is responsible for asynchronous communication between LKM and the IMS. The user interface is a WWW application that allows users to bind utility functions to various types of traffic. The WebUI also provides insight into statistics about transmitted traffic and network usage cost.

The DANUMS is implemented as a Linux LKM [5] and has to be installed and running on all of the client devices, that wish to participate in the CARMNET network. The implementation as a kernel module gives access to low-level networking stack. This is a crucial ability, as DANUMS manages the flow of packets with respect to their delay-aware Max-Weight Scheduling (MWS) weights [24] by means of custom queues and the corresponding scheduling system – as depicted in Figure 8. For the MWS algorithm to function correctly, information about queue levels is signalled throughout the CARMNET network by means of CARMNET-specific Layer-2 Queue-Level Estimation (L2QE) protocol.

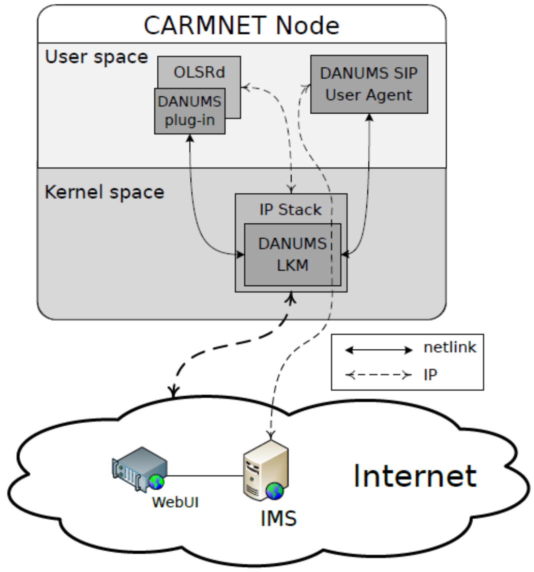


Figure 7. Overview of CARMNET system architecture.

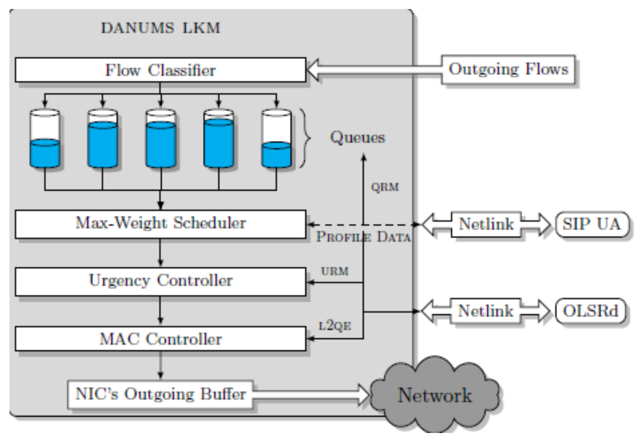


Figure 8. A single CARMNET mobile node subsystem implemented as LKM [35].

Other protocols are used internally in the CARMNET network to measure network delay (Delay Reporting Protocol, DRP), exchange information about currently forwarded flows (Queue Reporting Protocol, QRM) and for exchanging information on urgency scheduling weights (Urgency Reporting Messages, URM).

### E. *IMS-Based Support for Utility-Based Charging*

Typically, CARMNET users are the ones that do not have the direct and acceptably cheap access to 3G/4G network. It is assumed that virtual utility units, after being earned by users sharing their mobile Internet access with other users of CARMNET-based wireless networks, may be spent by these users ('potentially altruistic', i.e., risking the lack of a reward for sharing the Internet connection) for accessing mobile Internet connection shared by other users.

The original CARMNET concept of the utility-based charging is based on a combination of charging per traffic volume and traffic volume virtualization based on the mechanism of explicit transfer of virtual units that has been proposed as the key element of the Delay-Aware NUM System (DANUM) framework [5]. The realization of the concept is supported by efforts put on the integration of the DANUM system with an IMS-compliant AAA system [6], [15].

The CARMNET architecture assumes extending an open implementation of the IMS server infrastructure (OpenIMSCore) by the SIP servlet located on the Application Server (AS). The communication between the network nodes and the IMS Server is realized with the use of SIP User Agent (a lean SIP client application).

CARMNET-DANUM system has been made fully compatible with the interfaces of the IMS core servers [6]. Information on flows' utility is signalled in the network by the SIP User Agent and sent to the accounting server on the IMS platform. Implementing a fully featured IMS server based on OpenIMSCore [36] eliminated the need for developing a core telecom infrastructure from scratch, at least as long it is understood as a combination of user management, session handling and AAA functions [15].

### F. CARMNET-XML Protocol

According to the vision of CARMNET, the standard session management functionalities provided by IMS core servers are used in a non-typical way - for the management of user-shared Internet access sessions (so called "CARMNET sessions") rather than, e.g., for the management of VoIP sessions. On the other hand, the standard AAA functionalities provided by IMS core are extended by additional CARMNET-specific features of utility monitoring that enable utility-based charging. These additional functionalities are provided in an IMS-complaint way, as a result of an implementation of SIP servlet and a special "CARMNET over SIP protocol" used for exchanging the information for the purpose of the utility-based charging. What is specific for CARMNET is that the IMS infrastructure is used to manage users profiles and to store the configuration of end-users' utility functions.

As shown in Figure 9 SIP protocol, as one of the basic constituents of the IMS architecture, has been selected for the CARMNET-XML protocol encapsulation [15]. On the server side, a SIP servlet that receives CARMNET XML messages has been implemented. The architecture of the IMS platform makes the set of CARMNET servlets easily extendable. The CARMNET-specific implementation of IMS assumes the use of a Representational State Transfer (REST) Web Service for the interaction between the AS and a CARMNET-specific user database, e.g., performed to update the amount of denarii 'possessed' by a given user. Functions of the CARMNET-XML protocol are illustrated in Figure 10.

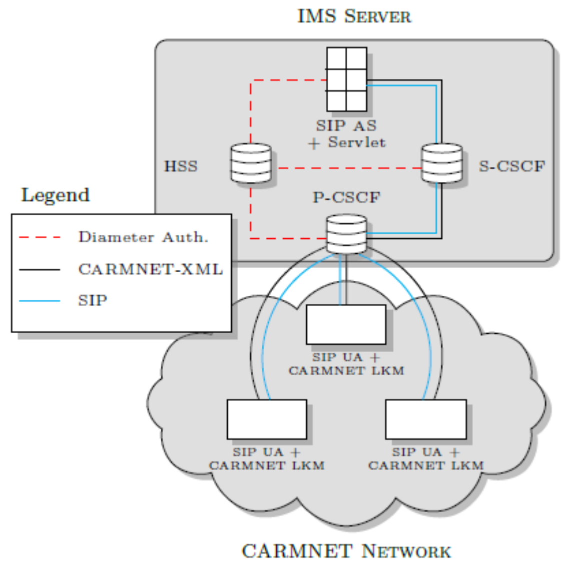


Figure 9. Integration of CARMNET system with IMS architecture [35].

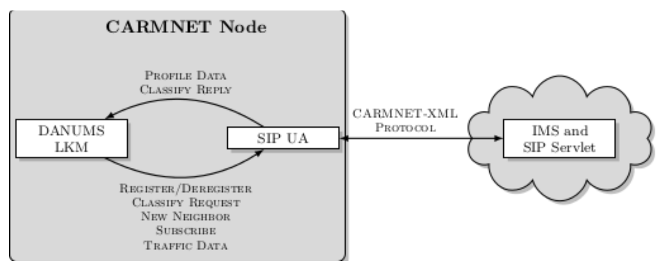


Figure 10. Functions of CARMNET-XML Protocol [35].

### G. Integration of Wireless Network Resource Management with Mobility Support

Since DANUM uses the OLSR protocol to send DRM messages [24], it cannot measure the delay of flows endpoints that are beyond a CARMNET network. DANUMS can measure the delay of such flows up to the Internet sharing node. Similarly, the accuracy of rate measurement for such flows is reduced. To fix these problems, the DANUMS Loadable Kernel Module (LKM) allows injection of measurements from external sources through procfs interface [11]. This interface is represented in Linux systems as a regular file, allowing both read and write operations [37]. DANUM system operates on per-flow basis, i.e., it measures the network performance parameters for each flow separately. Consequently, each line of the procfs file corresponds to a single flow managed by DANUM. In addition, DANUM allows supplying information regarding routes as well.

In a CARMNET network, mobility support is provided by the WiOptiMo [11], [38] framework. A CNAPT installed on any CARMNET wireless node provides mobility services to users who subscribed for them. It intercepts traffic flows associated to the mobility service and relays them to a SNAPT according to their requirements in terms of bandwidth and delay, in order to provide the desired Quality of Service (QoS). Multiple SNAPTs are located on the Internet to manage scalability and avoid concentrating traffic flows in a single spot.

WiOptiMo monitors the route between CNAPT and a SNAPT with a separate control traffic flow. Each CNAPT also periodically measures delay (one-trip time) and throughput (amount of received data over a time period) towards the different SNAPTs using this socket. The information gathered in the process can be passed to the DANUM LKM by writing it to the procfs file as flow measurement lines with reduced flow identifier consisting of source and destination IP addresses only. Implementation details about the format of each line can be found in [11].

Thanks to the procfs interface, WiOptiMo can provide measurements DANUM cannot perform. For example, a delay between a gateway and a SNAPT, measured by a CNAPT, can be added to the delay of flows destined to that SNAPT and leaving the CARMNET network through that gateway, in order to enhance the accuracy of measurements used in utility calculation. Furthermore, since a SNAPT can be installed on the same device of the flow endpoint or on a different device of the same network, the accuracy of measurements used by DANUM in the calculation of utility for flows that are outside a CARMNET network can be exactly estimated. A CNAPT on the source node can also overwrite throughput measurements for flows which it is responsible for, to account for losses encountered outside of the CARMNET network.

The WiOptiMo framework also allows a mobile node of a CARMNET network to change gateway transparently (e.g., when node moves out of the reach of the initial gateway due to the mobility of the associated user), without suffering service disruption (mobility support). In typical use cases of wireless mesh networks, only Internet gateways have public IP addresses and use NAT to share this connection. If an Internet gateway changes, the already established connections will break. To avoid this, the most common practice is to route traffic through the old gateway, which is inefficient. WiOptiMo overcomes this limitation and allows public IP to be changed seamlessly. DANUM allows to use the best available route to the selected SNAPT, at all times, regardless of the currently selected gateway. This feature is implemented by DANUM without modifying the OLSR protocol and its implementation by introducing a "virtual" host entity into Topology Control OLSR messages, representing a connection between an Internet sharing node and a SNAPT as a link state information [7].

## V. MULTI-TESTBED EXPERIMENTATION

CARMNET solutions are being extensively evaluated in multiple experiments performed in several realistic testbeds, in particular in the ones located at CARMNET partners' facilities: the wnPUT testbed [39], the Polanka-net [23] and the SUPSI testbed. The experimentation efforts involve the remote use of a large-scale wireless testbed, the DES-Testbed. Experiments within the facilities of a public metropolitan WiFi operator have been performed as well [7].

### A. *wnPUT Testbed*

The wnPUT Testbed has been built mainly for the development and the experimentation related to carrier-grade resource management for heterogeneous traffic based on the DANUM approach [5]. The focus of this work is put on the core CARMNET software, such as DANUMS Loadable Linux Kernel Module, which requires more control over each node than development of applications run in the so-called Linux userspace [37].

The wnPUT testbed consists of a software framework for centralised control of the testbed, and hardware upon which experimental and management networks are built. The hardware part consists of 13 dedicated nodes allowing to conduct multiple uninterrupted iterations of experiments remotely, without additional assistance.

Each node is connected to a Power-over-Ethernet switch, allowing to remotely power-cycle the node, even if built-in watchdog fails to detect system failure. This feature is crucial for low-level Linux kernel development, such as implementation of routing and packet scheduling modules of the DANUM system [40]. Nodes themselves are built upon ALIX platform, very similar to the one used in one of the largest wireless experimental networks – the DES-Testbed [41], [42].

The software framework accompanying the hardware part of wnPUT testbed includes online monitoring and graphical analysis tools that allow for the real-time graphical analysis of each experiment. The system consists of two core elements:

- the reader of unified experiment data,
- the tool for graphical visualization of the data.

An example of the network topology observable in an experiment conducted in the wnPUT testbed is presented in Figure 11 - it has the form provided by the wnPUT Monitor. Plots representing changes of the key DUNUMS variables during one of experiments executed in the wnPUT testbed are shown in Figure 12. The set of the variables includes:

- queue level,
- flow rate,
- virtual traffic price,
- flow utility,
- flow utility change.

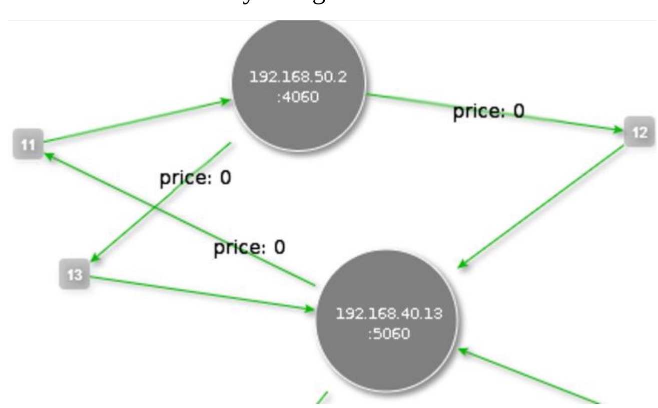


Figure 11. A view on the topology of an exemplary network shown in the wnPUT Monitor.

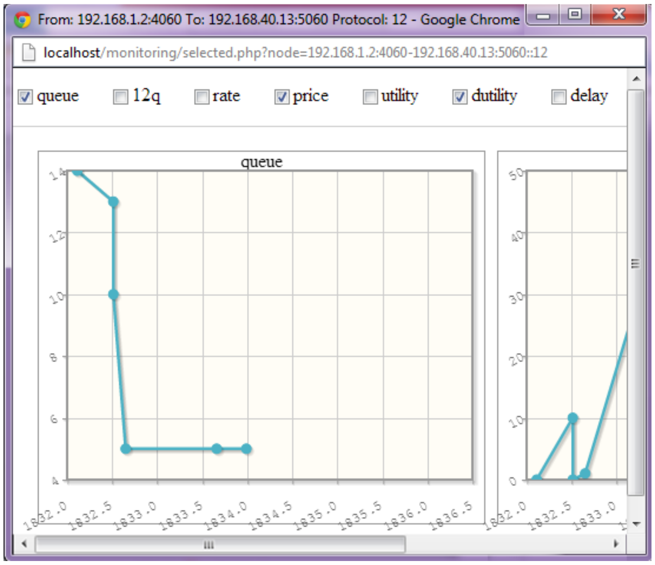

Figure 12. Graphs presenting the experiment results in wnPUT Monitor.

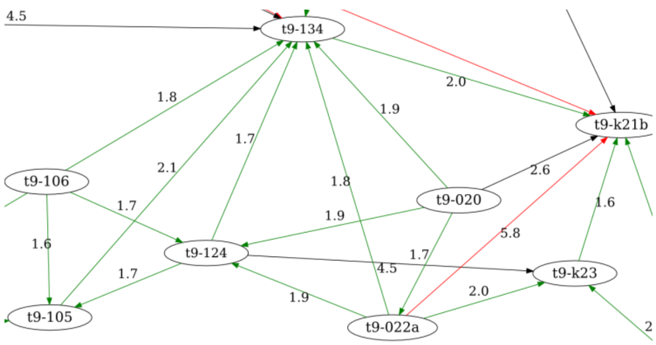

Figure 13. Sample topology fragment, generated based on ETX metric by wnPUT topology monitoring tool.

Figure 13 shows a part of wireless network topology generated by the wnPUT topology monitoring tool on the basis of the ETX metric supplied by OLSRd and monitored on one of the testbed nodes [40].

The wnPUT testbed uses an extended DES-Cript — a domain specific language for the testbed experimentation developed at Freie Universitat Berlin [43]. Instead of developing another experiment description, we have opted to use the already established DES-Cript. Thanks to DES-Cript being based on XML, we were able to further extend capabilities of the experiment description while preserving the ability of executing pure DES-Cript scenarios. For additional features, such as remote power-cycling of nodes, we use in-house extensions of the experiment description syntax.

### B. *Polanka-net Testbed*

The Polanka-net testbed was designed for testing the modified OLSR protocol based on the proposed multi-criteria *k*-shortest path algorithm [26]. The architecture of Polanka-net testbed is shown in Figure 14. The main part of the testbed consists of 12 nodes equipped with dual-core Intel ATOM processors. Each of them is equipped with: a solid state drive with the capacity of 24 GB, 4 GB of RAM and double core ATOM CPU (Central Processing Unit). The presented node's configuration allows for installing Linux in both "server" and "desktop" versions. The nodes are of small size, comparable to the dimensions of the nodes used in wnPUT testbed.

The main advantage of x86 nodes with ATOM CPUs is reasonable computing power and the fact that the developing software for this kind of nodes does not require cross-compilation. The source code can be compiled directly on the developer's workstation or within the node. The simplest solution for x86 nodes is the native compilation of the software at the nodes. In the case of native compilation, it is only required to provide the node with a source code.

The use of the nodes that were built using x86 processors (hereinafter referred to as x86 nodes) facilitates the implementation of the software. However, such nodes are more expensive and consume more energy with respect to the nodes using Reduced Instruction Sets Computer (RISC) processor. This fact was taken into account when the Polanka-net testbed was designed. Consequently, the testbed allows using low-cost nodes based on RISC CPUs (RISC nodes in Figure 14). The concept of using low-cost nodes was presented in the article [23].

The RISC nodes, used in Polanka-net testbed, support OpenWRT [44]. Open WRT is a Linux distribution dedicated for routers. It is characterized by small hardware requirements, since a firmware image (including kernel but without WiFi support) often does not occupy more than 2 MB of memory. One of the main advantages of the Open WRT is its ability to run on wide variety of processor architectures. This is possible owing to the fact that the software has an open code, which can be compiled into binary code designed for a specific platform.

In order to facilitate the implementation of multi-criteria algorithm, a special approach was applied: new discovered routes are added to the system routing table via a separate module. This module uses Zebra protocol to communicate with the OLSR protocol and its path computing algorithm. The Zebra protocol's messages are exchanged using TCP connections. The extension of Zebra's functionalities allows us to use RISC node without implemented OLSR protocol software. The OLSR protocol may be supported by the dedicated server. Consequently, the functionality of RISC nodes is limited to two tasks only. The first task is related to forwarding IPv4 packets according to the rules written in the routing table. This task is performed by the Data Plane. The second task is related to sending, receiving, forwarding and processing OLSR messages. In the proposed solution, the control plane OLSR server does not have direct access to the nodes' interfaces. In order to send or receive OLSR protocol messages via specified interface, the control plane OLSR server has to send them to the nodes, via appropriately modified Zebra protocol.

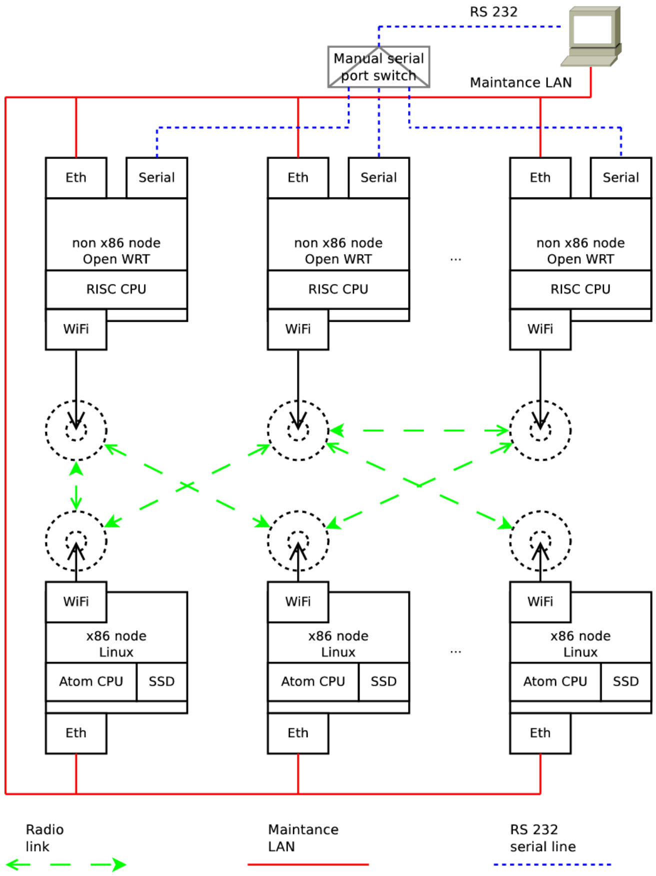


Figure 14. Polanka-net Testbed.

## C. SUPSI Testbed

The SUPSI testbed was designed to test the performance of the CARMNET mobility module based on the WiOptiMo framework. It contains three static (two of which are Internet-sharing) nodes and two wireless mobile network nodes. Each static node consists of an ALIX.2D2 system board, which supports two mini-PCI radios. We used one Wistron DNMA92 miniPCI card for each board, which is in turn connected to a two 802.11n antennas. Each board has a 500 MHz AMD Geode LX800 processor and 256 MB DDR DRAM. We installed Debian Wheezy (7.0) on each node with Linux Kernel 3.12.6 and used driver ath9k for Wi-Fi. The two mobile nodes are two ASUS EeePC 900 with a Atheros 5008Wireless Card, a 900MHz Celeron Processor and 1GB DDR RAM. They run Debian Wheezy 7.0 as well, while the Wi-Fi driver is ath5k.

To complete the hardware setup, we installed WiOptiMo SNAPT on a Dell Optiplex 760 (server), while WiOptiMo CNAPT was installed on a Lenovo ThinkPad T410a. Both machines run a Linux distribution (Ubuntu 12.04). Two of the static nodes (gateways) and the server are connected to the Internet with an Ethernet 100Mbit/s connection, while the rest of the nodes are participating in the mesh network. Both the gateways perform NAT between the mesh network and the Internet. Optimised Link S tate Routing Protocol

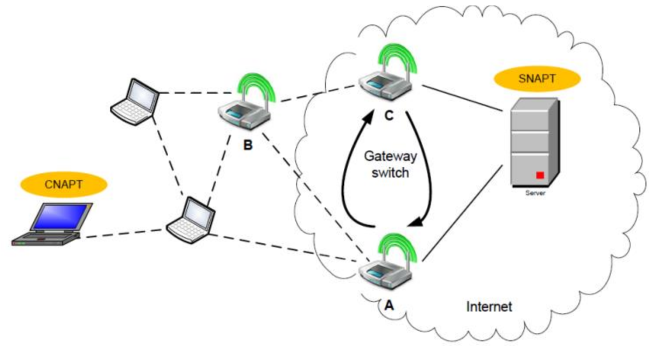


Figure 15. SUPSI testbed.

daemon (OLSRd, version 0.6.2) [12] runs on each node of the network for network path resolution. The final testbed architecture is illustrated in Figure 15.

## D. Experimental Application in a Public Wireless Network

Experiments presented in [7] describe the case of a CARMNET system being integrated with an existing, real-world public wireless network (WiFi Lugano network). As it has been demonstrated in the experiments, CARMNET solutions may be used to extend the network coverage and provide the unique features of network coverage extension and utility-aware seamless handover [7]. In particular, as presented in Figure 16 (depicting the network topology) and Figure 17, in the network coverage experiment, the nodes $n_1$ and $n_2$ (featuring the CARMNET DANUMS LKM) have enabled a mobile user to preserve the access to the Internet despite being out of WiFi Lugano's range.

The balance of virtual utility units (called denarii) presented in Figure 17 indicates how 'cooperation-oriented' each node was in sharing/using the Internet connection during the experiment. It may be seen that the user node, being the one initiating all the traffic was thus simply 'paying' for it: this can be seen in its constantly dropping denarii balance. The virtual unit balance of node $n_2$ oscillated around zero, since it was only forwarding the traffic originated in another node. The node $n_1$ has been immediately 'rewarded' for sharing its Internet access connectivity [7]. Moreover, the nodes $n_1$ and the user's node have provided the IMS Core servers with the CARMNET-specific data indicating the fairness of the user traffic relaying realized by the node $n_2$. On the basis of this data, the 'reputation' of the node $n_2$ may be automatically 'evaluated' and 'taken into account' by other nodes - not necessarily the same as those taking part in the session providing the data.

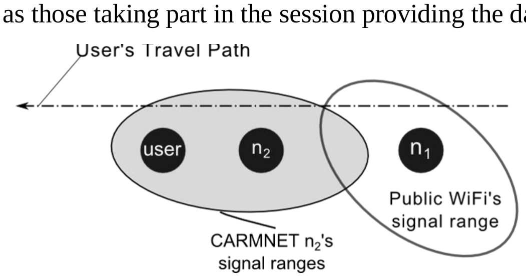


Figure 16. Network topology in the Internet access coverage extension experiment.

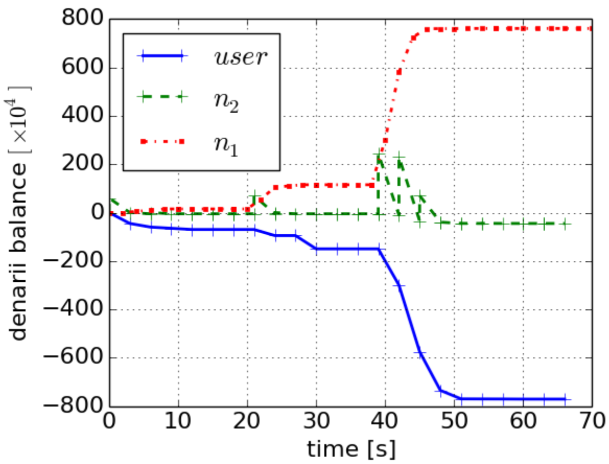


Figure 17. Denarii balance for the three CARMNET nodes during the Internet access coverage extension experiment [7].

## VI. Key Practical Results

To the authors' knowledge, the DANUMS system developed in CARMNET is the first delay-aware NUM solution practically interoperable with widely used protocols such as Transmission Control Protocol (TCP), User Datagram Protocol (UDP), Internet Protocol (IP), and 802.11 Media Access Control (MAC) [11]. The system is also the first NUM system integrated with the core IMS infrastructure [6], [15] and the first one that is capable to effectively operate in a public wireless network [7].

As demonstrated in experiments conducted in a physical testbed [15], the integration with the DANUMS (i.e., with a system responsible for wireless network resource management) has not compromised the performance of the IMS-compliant AAA functions. It may also be seen that the idea of developing a new protocol (i.e., CARMNET-XML protocol for the CARMNET specific registering and signalling) as an extension of SIP protocol, has proven to be a good choice, as far as the key user-perceived performance metrics are concerned [15], [35]. In particular, the addition of CARMNET-specific functions based on SIP communication, has not introduced a significant user registration delay, nor a significant protocol encapsulation overhead, necessary for the CARMNET-specific transmission quality reporting (allowing to maximize the network utility in a delay aware way) [15]. On the basis of such observations, it may be concluded that the proposed SIP-based approach to the access management and the user information exchange, while being compliant with the widespread IMS technology used in many telecom operators' networks [35], is indeed a viable mean for utility-maximizing local wireless network management [15].

## VII. Conclusion

In our opinion, CARMNET is a project worth a significant interest of researchers working in – so far rather distinct – areas of wireless mesh networking and IMS-based session and user management. Moreover, the practical importance of the project research objectives seems to be in line with the recent trend of deploying wireless Internet access sharing by commercial service providers and telecom operators [35]. CARMNET-like networking provides many benefits for service providers, e.g., increases network coverage without the need for extending the hardware infrastructure [7]. CARMNET architecture makes no assumptions regarding the kind of the Internet access connection, although naturally it is more likely to be deployed in a network with a fixed line Internet access, as it is usually cheaper and provides higher throughput than mobile Internet access.

It is worth being noted that in contrast to existing services, the implementation of CARMNET technological solutions, in particular the Delay-Aware Network Utility Maximization framework [5], enables to share the Internet access within a community of users truly delay-aware and QoS-oriented. In particular, a visiting user may be served in accordance to both his/her current demands (meeting of which is reflected by the rate of spending of virtual currency units) and the access point owner's willingness to share his/her WiFi network and the Internet connection.

Mainly as a result of the scenario-based design methodology [22] most of CARMNET solutions, although at a glance possibly appearing as purely technological, stay in a close correspondence to the project vision. In particular, a one-to-one correspondence appears between the delay-dependent traffic transport utility perceived by the visiting user (innovatively reflecting both the average effective throughput and the transmission delay characteristics) and the rate at which virtual currency units are earned by the owner of the local network infrastructure. In other words, we assume that each user should be awarded (in terms of virtual currency earnings) for his/her network resources sharing, and that this should be done in a way reflecting the user's subjective experience of the network access fairness. We believe that this is the right way in which the owners of high-quality and/or conveniently located network facilities may be motivated to share a significant part of their resources with many satisfied members of the CARMNET-enabled network access sharing community.


## Acknowledgment

This work was supported by a grant CARMNET financed under the Polish-Swiss Research Programme by Switzerland through the Swiss Contribution to the enlarged European Union.


## References


[1] M. Glabowski and A. Szwabe, "Carrier-grade Internet access sharing in wireless mesh networks: the vision of the CARMNET project," Proc. The Ninth Advanced International Conference on Telecommunications (AICT 2013), pp. 113-116, 2013.

[2] "CARMNET project website," [Online]. Available from: http://www.carmnet.eu 2014.05.30.

[3] V. Chandrasekhar, J. Andrew, and A. Gatherer, "Femtocell networks: A survey," IEEE Comm. Magazine, vol. 46, no. 9, pp. 59-67, Sep. 2008.

[4] I. Akyildiz, X. Wang, and W. Wang, “Wireless mesh networks: A survey,” Computer Networks, vol. 47, no. 4, pp. 445-487, 2005.
[5] A. Szwabe, P. Misiorek, and P. Walkowiak, “Delay-aware NUM system for wireless multi-hop networks,” Proc. 17th IEEE European Wireless 2011, EW2011, Vienna, 2011.
[6] P. Walkowiak, M. Urbanski, A. Figaj, and P. Misiorek, “Integration of DANUM-based carrier-grade mesh networks and IMS infrastructure,” Proc. Ad-hoc, Mobile, and Wireless Networks, Lecture Notes in Computer Science, vol. 7960, pp. 185-196, 2013.
[7] P. Walkowiak, R. Szalski, S. Vanini, and A. Walt, “Integrating CARMNET system with public wireless networks,” Proc. The Thirteenth International Conference on Networks, Nice, February 2014.
[8] S. Rayment and J. Bergstrom, “Achieving carrier-grade Wi-Fi in the 3GPP world,” Ericsson Review, 2012.
[9] A. Banchs et al., “CARMEN: Delivering carrier grade services over wireless mesh networks,” Proc. PIMRC 2008, Sep. 2008.
[10] P. Walkowiak, M. Urbanski, M. Poszwa, and R. Szalski, “Flow classification in delay-aware NUM-oriented wireless mesh networks,” Proc. The Sixth International Conference on Advances in Mesh Networks, Barcelona, 2013.
[11] S. Vanini, D. Gallucci, S. Giordano, and A. Szwabe, “A delay-aware NUM-driven framework with terminal-based mobility support for heterogeneous wireless multi-hop networks,” Proc. ICTF 2013 Information and Communication Technology Forum, I-scover, IEICE, 2013.
[12] “An ad-hoc wireless mesh routing daemon,” 2009. [Online]. Available from: http://www.olsr.org. 2014.05.30.
[13] A. Szwabe, P. Misiorek, A. Nowak, and J. Marchwicki, “Implementation of backpressure-based routing integrated with Max-Weight Scheduling in a wireless multi-hop network,” Proc. IEEE 35th Conference on Local Computer Networks (LCN), Oct. 2010.
[14] T. Clausen and P. Jacquet, “Optimized Link State Routing Protocol (OLSR),” Internet Engineering Task Force, 2003. [Online]. Available from: http://www.ietf.org/rfc/rfc3626.txt 2014.05.30.
[15] P. Misiorek, P. Walkowiak, S. Karlik, and S. Vanini., “SIP-Based AAA in delay-aware NUM-oriented wireless mesh networks,” Image Processing and Communications, vol. 18, no. 4, pp. 45-58, 2013.
[16] H. Khartabil, A. Niemi, M. Poikselka, and G. Mayer, “The IMS: IP multi-media concepts and services in the mobile domain,” Wiley, 2004.
[17] “Orange FunSpot,” [Online]. Available from: http://www.funspot.orange.pl/ 2014.05.30.
[18] “Fon,” fon, [Online]. Available from: https://corp.fon.com 2014.05.30.
[19] “Netia,” Netia, [Online]. Available from: http://www.netia.pl/ 2014.05.30.
[20] M. Chen, M. Ponec, S. Sengupta, J. Li, and P. A. Chou, “Utility maximization in peer-to-peer systems,” Proc. The 2008 ACM SIGMETRICS International Conference on Measurement and Modeling of Computer Systems, Annapolis, MD, USA, June 02-06, 2008.
[21] C. Middleton and A. Potter, “Is it good to share? A case study of FON and Meraki approaches to broadband provision,” Proc. International Telecommunications Society 17th Biennial Conference, Montreal, 2008.
[22] J. Carroll and R.H.J. Sprague, “Five reasons for scenario-based Design,” Proc. The 32nd Annual Hawaii International Conference on Systems Sciences, 1999.
[23] A. Kaliszan and M. Głąbowski, “An environment for implementing and testing routing protocols in CARMNET architecture,” Proc. The The Ninth Advanced International Conference on Telecommunications (AICT 2013), Rome, 2013.
[24] A. Szwabe, P. Misiorek, and P. Walkowiak, “DANUM system for single-hop wireless mesh networks,” Proc. The 2010 International Conference on Future Information Technology (ICFIT 2010), Changsha, China, Dec. 2010.
[25] A. Brander and M.C. Sinclair, “A comparative study of k-shortest path algorithms,” Proc. 11th UK Performance Engineering Workshop, 1995.
[26] D. Eppstein, “Finding the k shortest paths,” SIAM Journal on Computing, vol. 28, no. 2, pp. 652-673, 1998.
[27] C. Clímaco, M. Pascoal, M. Craveirinha, M. Eugénia, and V. Captivo, “Internet packet routing: Application of a K-quickest path algorithm,” European Journal of Operational Research, vol. 181, no. 3, pp. 1045-1054, Sep. 2007.
[28] A. Szwabe and P. Misiorek, “Integration of Multi-path Optimized Link State Protocol with Max-Weight,” Proc. IEEE International Conference on Information and Multimedia, Jeju Island, South Korea, 2009.
[29] M. de Vega Rodrigo and R. Pleich, “Validation and extension of the M/G/R Processor Sharing to dimension elastic traffic in TCP/IP networks,” Proc. The 2nd Polish-German Teletraffic Symposium, Gdansk, 2002.
[30] J. Roberts and T. Bonald, “Internet and the Erlang Formula,” ACM Computer Communications Review, vol. 42, no. 1, pp. 23-30, 2012.
[31] T. Bonald and J. Virtamo, “A recursive formula for multirate systems with elastic traffic,” IEEE Comm. Letters, vol. 9, no. 8, pp. 753-755, 2005.
[32] G. Stamatelos and V. Koukoulidis, “Reservation-based bandwidth allocation in a radio ATM network,” IEEE/ACM Transactions on Networking, vol. 5, no. 3, pp. 420-428, 1997.
[33] S. Hanczewski, M. Stasiak, and J. Weissenberg, “The queueing model of a multiservice system with dynamic resource sharing for each class of calls,” Proc. Computer Networks, Springer, 2013, pp. 436-445.
[34] S. Hanczewski, M. Stasiak, and J. Weissenberg, “A queueing model of a multi-service system with state-dependent distribution of resources for each class of calls,” IEICE Transactions on Communications, in press, 2014.
[35] R. Szalski, A. Szwabe, and P. Misiorek, “Flow utility estimation and signaling in a CARMNET network,” Institute of Control and Information Engineering, Poznan University of Technology, Technical Report no 657, Poznan, 2014.
[36] “OpenIMSCore,” [Online]. Available from: http://www.openimscore.org/. 2014.05.30.
[37] B. Wang, B. Wang, and Q. Xiong, “The comparison of communication methods between user and kernel space in embedded Linux,” Proc. International Conference on Computational Problem Solving, 2010.
[38] S. Giordano, D. Lenzarini, A. Puiatti, and S. Vanini, “WiSwitch: seamless handover between multi-provider networks,” Proc. WONS 2005, 2005.
[39] A. Nowak, P. Walkowiak, A. Szwabe, and P. Misiorek, “wnPUT Testbed experimentation framework,” Distributed Computing and Networking, Lecture Notes in Computer Science, vol. 7129, pp. 367-381, 2012.
[40] R. Szalski, et al. “D3.1: The report on testbed set-up and performance measures specification, CARMNET project deliverable (internal report),” 2013.

[41] M. Gunes, F. Juraschek, B. Blywis, and J. S. Q. Mushtaq, “Testbed for next generation wireless network research,” Special Issue PIK on Mobile Ad-hoc Networks, vol. 34, no. 4, 2009.
[42] “DES-Testbed,” [Online]. Available from: http://www.des-testbed.net/ 2014.05.30.
[43] M. Gunes, F. Juraschek, B. Blywis, and W. Olaf, “DES-CRIPT - a domain specific language for network experiment descriptions,” Proc. The International Conference on Next Generation Wireless Systems, Melbourne, 2009.
[44] “OpenWRT,” [Online]. Available from: https://openwrt.org/ 2014.05.30.