Integrating CARMNET System with Public Wireless Networks

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***Abstract*—In this paper, we present two scenarios of the CARMNET system application in wireless networks. The CARMNET system is an advanced experimental resource allocation framework based on the Network Utility Maximization model that may be integrated with a standard telecom operator infrastructure. Having developed the CARMNET system, we tested it in a publicly available wireless network, operated by the city of Lugano, Switzerland. In the presented scenarios, the CARMNET was employed to extend the network coverage and to improve it by providing the feature of seamless handover. The results indicate the ability of successful integration of the CARMNET system with an existing real-world network.**

***Keywords*-Wireless Mesh Networks; Network Utility Maximisation; network scalability; DANUMS; seamless handover**

I. Introduction

The main idea behind the *Carrier-grade delay-aware resource management for wireless multi-hop/mesh networks* (CARMNET) [1] system is to make the user-provided Internet access a viable alternative to the currently widespread 3G/4G-based mobile Internet access. Simultaneously, the CARMNET system introduces an advanced, distributed resource management mechanisms integrated with a telecom operator's IP Multimedia Subsystem (IMS) and Authentication, Authorisation and Accounting (AAA) infrastructure and provides support for generalized network node mobility. Put into practice, these ideas allow us to improve existing, wireless networks with features like transparent extension of range and better network resource utilisation.

A. Drawbacks of traditional wireless networks

Traditional networks, including wireless ones, require hardware investments in order to scale. To support more users and provide a larger network range, wireless access points must be either upgraded, or their number simply has to be increased. The issue is even more noticeable the higher the number of users and the wider the required coverage. However, the cost of new hardware is not the only one. There is also the price of additional service and management. The proposed system shifts the costs of the hardware towards the users of the network, giving in return benefits to those users who share their network access. Another issue of standard wireless networks is that they seldom incorporate any resource management system, the lack of which may lead to degradation of user experience. This is particularly evident in cases when many users, with different delay and throughput requirements, are connected to the network at the same time. For example, if one of them establishes a Voice over IP (VoIP) connection (delay sensitive flow) and the other downloads a large file via File Transfer Protocol (FTP) (throughput demanding flow), the characteristic of FTP protocol will cause the decrease of the VoIP call quality and dissatisfaction of its recipients. Most of Internet providers deal with the problem by limiting the available throughput to the user or by blocking unwanted services. However, the CARMNET system, thanks to the adoption of the Delay-aware Network Utility Maximisation (DANUM) [2] framework and the introduction of applications' and users' specific profiles, can serve heterogeneous traffic according to its requirements [3]. This allows the delay of VoIP call to be minimized and the throughput of file transmission to be maximized, while providing a high level of user experience in both cases. Finally, the extension of the network's range can be achieved using a mobile node sharing its Internet access with remote nodes. The switch should be done transparently, ensuring the correct routing of packets without degradation of QoS perceived by the users. Thanks to the integration with the WiOptiMo framework [4], the CARMNET system is able to manage this scenario as well.

In this paper, we describe two scenarios where the CARMNET system was integrated with the Lugano WiFi network infrastructure. Each scenario is presented with a description of a real-world use case of the CARMNET architecture and its advantages. Issues regarding the integration of the CARMNET system into an existing wireless networks are presented in Section IV. The CARMNET system itself is thoroughly described in Section III. To validate our system

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integration, we executed field tests, since this approach allows to uncover most of the problems and it is also more adequate from integration perspective. Lugano, Switzerland, was chosen for our tests. It is a city of $65,015$ inhabitants and an area of $75.81\ km^2$. Free WiFi access is available for tourists in the city centre. Details about the configuration of the Lugano WiFi network are presented in Section V. To test the integration outcome, we carried out two experiments (described in Section VII), whose results are presented in Section VIII. It is important to highlight that although the experiments were performed in Lugano, the CARMNET system can be easily integrated with any wireless WiFi infrastructure.

II. Related Work

Many resource allocation systems based on the Network Utility Maximisation (NUM) model exist [5]–[7] and determine the utility of flows according to their measured properties. However, only a few of them were implemented and tested in a real wireless mesh network [5], [6]. It is an important step in an attempt to integrate proposed solutions with public networks. Unfortunately, such approaches were not sufficient to effectively measure the utility of both delay-sensitive and throughput-oriented flows. The system proposed in [2](DANUM System (DANUMS)) takes both parameters into consideration. Moreover, DANUMS has a well-tested implementation, which allows researchers to focus on specific parts of the CARMNET system.

Network mobility support is addressed in RFC 4886 [8] and in several architectural solutions presented in literature. SyncScan [9] is a Layer-2 procedure for intra-domain (between Access Points (APs)/same domain) handoff in 802.11 infrastructure mode networks. It achieves good performance at the expense of a required global synchronization of beacon timings between clients and access points. iMesh [10] provides low handoff latency for horizontal (same network technology) Layer-3 handoffs in Wireless Mesh Networks (WMNs). Its main drawback is that handoff delay depends on the number of nodes along the path between the new AP and the old AP. BASH [11], focuses on the design of a horizontal—intra-domain—Layer-2 seamless handoff scheme for 802.11 WMNs. BASH's main drawback is that it requires modifications on the mobile client's side for managing the handoff protocol. The method proposed in [12] uses tunnelling, as it is the case with RFC 4886 and the standard Mobile IPv6 solution [13]. Tunnelling introduces extra delay for the encapsulation/decapsulation of packets and has low flexibility intrinsically. Finally, SMesh [14] provides a 802.11 mesh network architecture for both intra-domain and inter-domain handoffs (between Internet-connected APs/different domains). For intra-domain handovers, SMesh generates high network overhead, which grows linearly with the number of clients. In case of inter-domain handovers, network overhead is directly proportional to the number of connections each client has.

III. CARMNET System

A. Integration of WMN and IMS

The integration of WMNs and IMS infrastructure provides many benefits for both users and telecom operators. WMNs enable extended network coverage without the need to expand the static infrastructure. At the same time, telecom operators may easily manage users and offer them additional services. In the presented solution, Session Initiation Protocol (SIP) is used as an integration protocol. Each node acts as a SIP User Agent (SIP UA). SIP, however, is designed to control access to the mesh network only. The IMS infrastructure is used for authentication, authorization, storage of user profile information as well as for accounting and charging. The registration is performed by the SIP UA implementing the authentication/authorization functions of IMS AAA by means of the standard SIP REGISTER message. The SIP SUBSCRIBE/NOTIFY mechanism has been applied to transport the user-related information.

B. The Architecture of the System

The architecture of the CARMNET system [1], [15] consists of multiple components located both on the client- and server-side (see Figure 1).

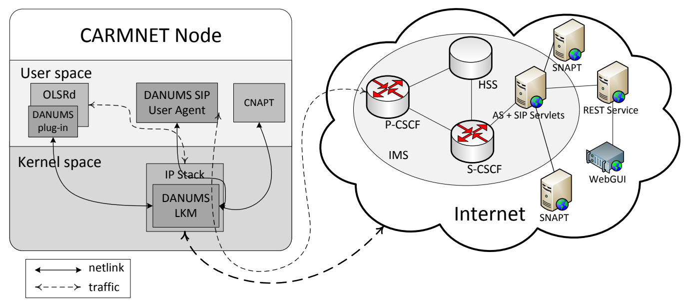

Figure 1: Interactions between CARMNET components.

DANUMS Loadable Kernel Module (LKM) [2] is an implementation of the DANUM model developed for the Linux environment. This subsystem works at the kernel level, which allows for a deep integration in the networking stack, necessary to introduce custom queuing and scheduling subsystems. For the network path resolution, the Optimised Link State Routing Protocol daemon (OLSRd) — a popular implementation of the Optimised Link State Routing Protocol (OLSR) protocol — is used. Since OLSR messages' additional purpose is to distribute data needed by the packet scheduler, a special way of communication between user-space (OLSRd) and kernel-space (DANUM LKM) had to be applied. The Netlink protocol serves that role. Network mobility support is performed by the CARMNET mobility subsystem, which is based on the WiOptiMo framework. A client proxy (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 server proxy (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. The WiOptiMo framework is also used for providing the DANUMS LKM with throughput and delay measurements for flows endpoints that are beyond the CARMNET network. This is done through *procfs* interface [16]. The direct communication of DANUM LKM located at the client's node with the IMS infrastructure located in a network is a difficult task. A high-level SIP protocol in the low-level kernel module has to be implemented, in a way that preserves the high efficiency of the Linux kernel. Therefore, we have developed a SIP UA in the user-space running on the client side, which is responsible for asynchronous communication between LKM and IMS. The communication between LKM and SIP UA is realized using the Netlink protocol, whereas the communication between SIP UA and IMS is realized using the custom CARMNET protocol, based on XML encapsulated in the standard SIP messages. This allows the design to be further compatible with the IMS architecture. The Web User Interface (WebGUI) is a WWW application dedicated to users of the CARMNET network. Users are allowed to configure their own profiles and to bind the utility function (and its arguments) to the type of traffic (e.g., WWW, e-mail, Skype). Moreover, WebGUI shows the utility unit account balance and reports about transmitted traffic and its 'price' in virtual currency. The concept of virtual currency (Denarii) is described in detail in Subsection VI-C. Two types of servlets are located on the application server. The first one is responsible for managing AAA functions and user profiles in the CARMNET network. After connecting to the network, each client has to be authenticated and authorized in the SIP servlet before starting an Internet session. During the session, each node in the network reports to the SIP servlet the amount and the type of traffic it has served. All CARMNET-specific information about users is accessible through the second servlet. As the information transport protocol, the servlet implements REST-like service and WebGUI acts as a REST client. To be part of the CARMNET network, users must install the abovementioned, client-side software, on their devices.

IV. Integration with Existing Networks

In general, there are two different approaches to integrating systems, such as CARMNET, into 3rd party, already established network solutions. The first one limits the integration to the network clients only, but reuses existing network's AAA system at the same time. This approach is aimed mainly at the extension of range of an existing wireless network, so that it covers the previously inaccessible areas, without the use of any additional static infrastructure. This is achieved by deploying additional software on clients' devices only. This software is responsible for advanced resource management as well as for network access sharing and has to be installed by all the connecting clients. As mentioned above, the optimization of resource usage is done in a distributed way by each of the CARMNET-compatible network components. In this scenario, optimization is performed locally, between clients' nodes and not throughout the network. Access points are not modified. Advantages of the CARMNET system are most visible when the DANUMS-enabled client shares its connection to another client.

The second approach, requires an additional modification to the software of the existing infrastructure, i.e., DANUMS has to be installed on all access points. Besides expanding the range and optimizing local resource usage, the CARMNET system provides a distributed optimization across the entire network. Another requirement of the CARMNET system is the integration with the existing AAA subsystem, which is necessary to allow clients to set up their profiles via the CARMNET WebGUI. This way, a more flexible accounting system based on users' perception of flows utility might be applied. This integration relies on implementation of an additional authorization plug-in for the CARMNET IMS subsystem.

For real-world scenarios, the first approach is easier to integrate. Many already existing network infrastructures have well established AAA capabilities. Integrating with those would require additional implementation effort making the solution less interesting. Moreover, we are currently not prepared to support any other platform than the Linux-based one. Therefore, we have used the first approach, which is less complex and easier to be fully realized. Furthermore, many use cases (including our proposed scenarios) are still viable without full integration.

V. The Lugano WiFi Network Configuration

The Lugano WiFi network is available in different discontinuous areas of Lugano. For our experiments, we have decided to focus only on the city centre area which, due to the way it is covered, is more appropriate for the scenarios presented in this paper.

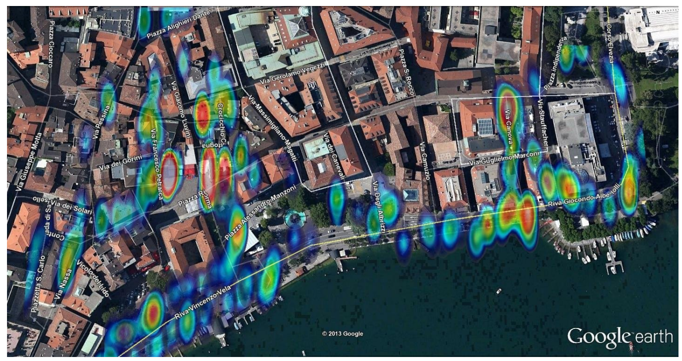

Figure 2: Lugano WiFi coverage in the city centre.

Figure 2 describes the actual configuration of the Lugano WiFi network in the city centre. It was obtained using the *Kismet* layer-2 wireless network detector to eavesdrop on 802.11 beacons and register the Global Positioning System (GPS) coordinates of the points where WiFi fingerprints were collected. In the picture, these points can be seen as circles with different colours, whose gradients vary from red, to yellow, green, and blue. They indicate gradual changes in Received Signal Strength (RSS), from strong to weak respectively.

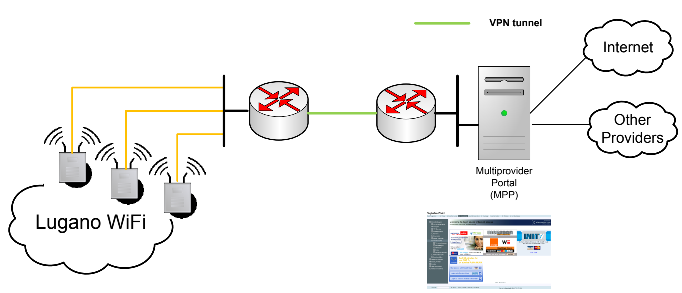

Figure 3: Lugano WiFi architecture.

The network is managed by the WLAN-Partner company [17], which is located in Zurich. The solution currently used

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by Lugano WiFi to manage handovers is based on tunnelling (Figure 3). A Virtual Private Network (VPN) tunnel is opened between the core router and the WLAN-Partner data centre. A software called Multiprovider Portal (MPP) performs AAA functions. It is based on the Linux application for packet filtering *iptables* and consists of a combination of rules and rulesets. Those rules mark the network traffic and determine if it belongs to an authorized session, with Internet access capability, or an unauthorized (new) session. In the latter case, traffic is redirected to a landing page. The MPP system allows each mobile client (identified by its Medium Access Control (MAC) address) to keep the same Internet Protocol (IP) address when moving and associating to a different access point. A lease tracker daemon checks for a session timeout, which is set to 30 minutes—after that time is elapsed, the user is redirected to the landing page and has to reconnect to access the network again. During the experiments, a set of special accounts without session time limit were used, for practical reasons. Finally, the average number of devices connected to the network is 1340 per month (about 45 per day), while the number of sessions per workday is 5050 and the average duration is about 25 minutes.

VI. CARMNET Usage Scenarios

A. Network Coverage Extension

Extending the range of static wireless networks requires the deployment of additional access points. This process is often complicated because of power or network infrastructure requirements. The CARMNET system allows for transparent extension of range using not only static infrastructure, but the clients' devices as well. Each user's device is equipped with the CARMNET client software, which enables the sharing of Internet access with other CARMNET clients. The process of sharing is managed by a resource management system, which takes care of the users' preferences in terms of how to serve their incoming and outgoing traffic. Additionally, our system introduces a unified charging system based on the transfer of virtual currency, which enables incorporation of a more complex model of incentives and collaboration enforcement (i.e., access to additional services). The Lugano WiFi network may provide coverage in locations where it previously was not possible. This would allow users to access the Internet even while being outside of the standard infrastructure. What might be especially beneficial to the telecom operators is the potential this scenarios has, to reduce last mile network operational costs. We can imagine a situation in which a single user is sharing Internet access to five other users. From the operator's perspective, the amount of bandwidth used by these six people is limited to the bandwidth accessible to the sharing user only. Another benefit is that each additional sharing user extends the signal range by the range provided by her device. Every network user and local facility, in public WiFi's range, can be a sharing node. Local facilities, since they are usually static, can continuously share the Internet connection.

B. Seamless Horizontal Handover

The CARMNET infrastructure can be used to bridge the gap between two (or more) scopes of WiFi signal. For this solution to be truly usable to the users, we need to provide handover functionality between the CARMNET network and the public WiFi. This way users' ongoing sessions will not be affected as they move from one device's WiFi signal range to the other. We have identified an uncovered area of the Lugano WiFi network and used CARMNET's sharing nodes to set up a simple WiFi network, and provide coverage in the indicated area (see Figure 4). The CARMNET's nodes were behind NAT gateways with different IP addresses. We wanted to test the capability to support WiFi micro-mobility (handover between access points of the same provider). For this purpose, a mobile CARMNET node moved linearly across the coverage area of the other CARMNET's sharing nodes. Using this configuration, we collected measurements about goodput, handoff latency (time to perform a complete handover procedure) and packets loss rate.

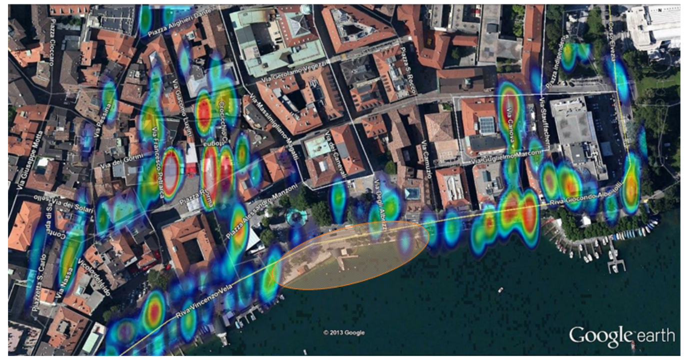

Figure 4: The area not covered by Lugano WiFi, chosen for the handover experiment.

C. The Usage of Virtual Currency

The CARMNET system provides a concept of virtual currency [2] called *Denarii*. It is used internally for flow management, but this is not its only possible use. In one scenario, it could be used for city promotion through discounts and vouchers for various attractions. Tourists may collect Denarii for selfless behaviour and turn them into various rewards, such as museum tickets. Cities could provide many other incentives for users, who would be encouraged to share their Internet connection. This would be beneficial to the whole network and local community.

VII. Experiments

Two experiments have been carried out on site, to verify the effectiveness of integration. Their results are presented in Section VIII. Before performing the experiments in the field, each one has been performed locally in a wireless network testbed [3] developed for CARMNET testing purposes. This testbed allows for an automated scenario execution using a set of ALIX integrated network nodes equipped with two network interfaces (a wired one for commands execution and a wireless one for experiment traffic). Those nodes are managed centrally using the wnPUT2 server capable of booting, restarting and issuing commands to groups as well as individual machines. This testbed helped us validate the following experiments.

A. Network Coverage Extension

An additional wireless CARMNET network, consisting of 3 nodes, has been set up. A stationary node n_1 was connected to Lugano WiFi network, during the whole experiment, and was acting as a final gateway for both nodes n_2 and the *user* node. Node n_2 was located such that it was connected to n_1 but was not in range of the public WiFi network. It had Internet access by means of Internet sharing from node n_1 only. The third node was simulating a user travelling along a linear path, from n_1, towards n_2 and beyond (see Figure 5). The user was initially connected to node n_1. While moving away from n_1, as the signal strength of n_1 lowered, it changed the default gateway to n_2. This was possible thanks to the OLSR daemon monitoring the Expected Transmission Count (ETX) routing metric extension, determining changes in path quality. Simultaneously, the user node lost the signal of public WiFi network. During movement, the user node was issuing Internet Control Message Protocol (ICMP) Echo Requests to an external address, reachable through the Internet, to check connectivity. At the end of the path, a Transmission Control Protocol (TCP) connection was established to download a 15 MB file using the *wget* application.

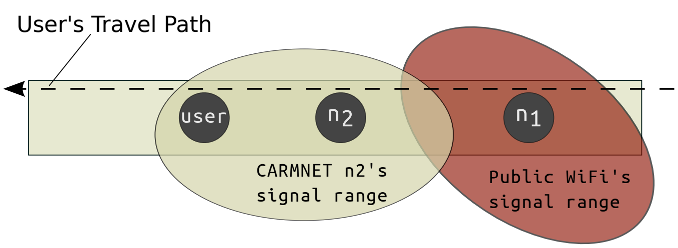

Figure 5: Network coverage extension experiment topology. Note that node n_1's signal range has been omitted for clarity.

B. Seamless Handover

There is a gap between signal ranges of the Public WiFi network at the experiment site. A CARMNET network, consisting of 3 nodes, has been set up to cover the signal gap. Nodes were arranged in a linear topology, so that the first (n_1) and last (n_2) nodes were connected to the Public WiFi network, to fill in the gap. Another, third CARMNET node was simulating a user travelling along the indicated path (see Figure 6). During its movement, it would eventually move out of the Public WiFi's signal #1 range. Since the mobile node was a CARMNET node, once the signal #1 strength decreased under a certain threshold, OLSRd automatically changed the routes and, as expected, the node was connected to the existing CARMNET network. A similar situation had taken place as the user node was leaving CARMNET network's range and approaching Public WiFi's signal #2 range. During the experiment, traffic logs across all of the nodes were collected.

VIII. RESULTS

The first experiment proved a successful extension of the Public WiFi network range, using the CARMNET system. Being connected to the CARMNET network, the user node was still able to access the Internet provided by Lugano WiFi, while being out of range of its infrastructure. No modifications

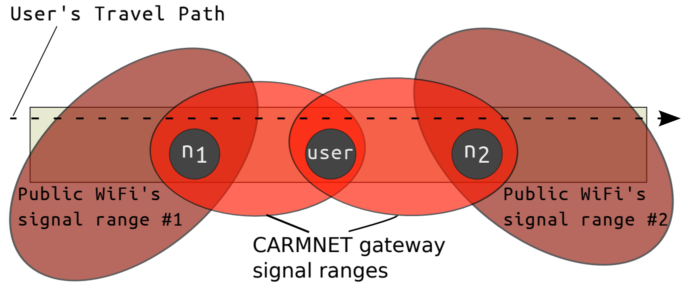

Figure 6: Handover experiment network topology.

to existing infrastructure were necessary. Figure 7 shows the Denarii balance over time for each node participating in the experiment, which indicates how much each node shared/used the Internet connection. User node was initiating all the traffic and thus paying for it: this can be inferred from a constantly dropping Denarii balance. Nodes n_2's virtual unit balance was oscillating around 0, since it was forwarding traffic only. It is worth noting, that ultimately, node n_1 was sharing the Internet connection for the rest of the nodes. It was thus rewarded by the CARMNET system with the highest amount of Denarii.

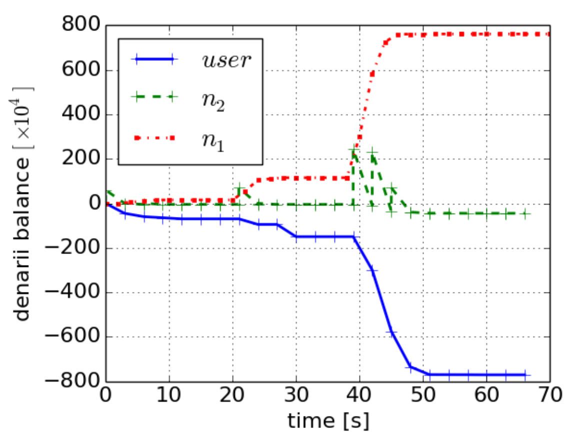

Figure 7: Denarii balance for the three CARMNET nodes during the first experiment.

Figure 8 shows a graph of TCP throughput for each of the CARMNET nodes participating in the second experiment. In the initial phase of the experiment, only node n_1 was in the range of the user node. It was thus chosen as a default gateway and shared Internet access from the Lugano WiFi network. As the user moved away from n_1, its RSS lowered and the default route began to degrade (the value of ETX metric was rising). During this time, all of the traffic was sent through node n_1, which can be seen in Figure 8. Around the middle of the experiment, user node began to detect signal from the second gateway (n_2). Once the alternative route had good enough ETX metric, the CARMNET mobility module based on WiOptiMo had switched routes. This corresponds to a gap in flow's throughput around 103rd second. The connectivity was not interrupted as the flow was forwarded by the second node n_2. The steep, brief increase in throughput, seen on the graph around 105th second, is caused by an accumulation of packets in the DANUMS queue after the handover has

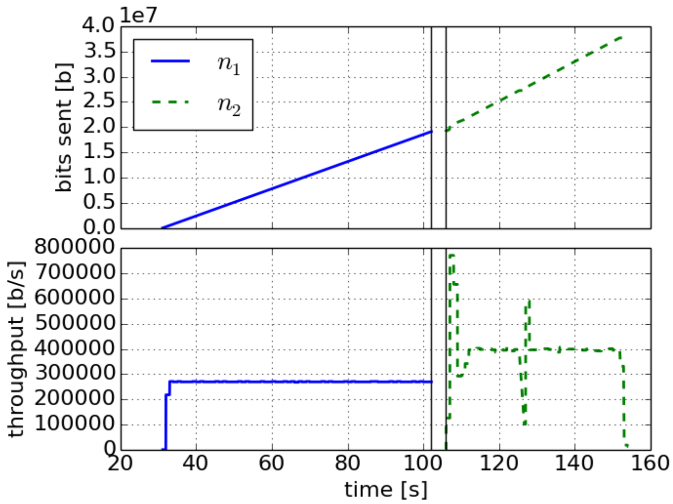

Figure 8: Throughput and total bits sent, registered at the 3 CARMNET nodes during the seamless handover experiment.

been completed. The overall goodput of the flow, measured during the experiment, was 1.01 Mbit/s. It took 3.78 seconds to complete the handover. Another metric is the rate of packet loss, which was around 0.21% during the transmission. From the above measurements, we can conclude that the handover was performed correctly and successfully.

IX. Conclusion and Future Work

We have shown that the CARMNET system can be successfully integrated into existing public wireless networks. Experiments presented in the paper illustrate the two most important real-word use cases of the system. The key factor enabling integration is the system's compatibility with standard AAA mechanisms used by the telecom operators such as the one implemented in the IMS platform. Even without modification of existing software, CARMNET provides many benefits for network users and Internet providers, e.g., network coverage increase, potential to reduce last mile operational costs and seamless handover.

In order to operate inside the CARMNET system, new users need an initial amount of virtual currency, which allow them to pay for their traffic when they have not yet got paid for serving flows themselves. Currently, new users are granted a fixed amount of Denarii. Our future work includes testing what amount of initial virtual currency is appropriate. It cannot be too small, because sharing users would not have a chance to earn enough, which might lead to a deadlock. It cannot be too big, since users would not be compelled to earn Denarii and thus share the Internet access. There is also the risk that users will not be paid for Internet sharing [1]. Our aim would be to minimise this risk by incorporating trust mechanisms akin to those implemented in Peer-to-Peer (P2P) networks.

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