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MONROE

Measuring Mobile Broadband Networks in Europe

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Final Implementation

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Abstract

This report describes the updates on the platform's final implementation with extensions and modifications. Specifically, the document describes the web user interface, the scheduling system, the management and maintenance system, the software running on the MONROE nodes (core components, default experiments and EaaS infrastructure, the repositories and data importer, the central database and the online visualization tool).

Participant organisation name	**Short name**
SIMULA RESEARCH LABORATORY AS *(Coordinator)*	SRL
CELERWAY COMMUNICATION AS	Celerway
TELENOR ASA	Telenor
NEXTWORKS	NXW
FUNDACIÓN IMDEA NETWORKS	IMDEA
KARLSTADS UNIVERSITET	KaU
POLITECNICO DI TORINO	POLITO

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1 Introduction

The main goal of MONROE is to build and operate a platform to conduct measurements and execute experiments on operational mobile networks. This document describes the platform implementation at M24, which not only addresses the initial technical problems of the prototype platform but also implements new features and extensions based on the feedback from the first open call external users. Although WP1 is concluded with this deliverable, MONROE consortium is committed to improve the platform by fixing the bugs as well as adding new features based on external user's requests. These will be addressed under the Maintenance Work Package (WP4) until the end of the project.

The MONROE platform is composed of the following elements, which are also summarized in Figure 1:

- MONROE hardware nodes.
- Core software running in the nodes, including the management and scheduling systems.
- Base experiments running in the nodes.
- Synchronization modules that send data to the servers.
- Server-side software to collect data from the internal experiments and store them in databases.
- Server-side scheduling of experiments.
- Server-side scripts for data backup and database dump.
- Server-side software for node management and maintenance.
- Server-side experiment scheduling components.
- WEB user interface.

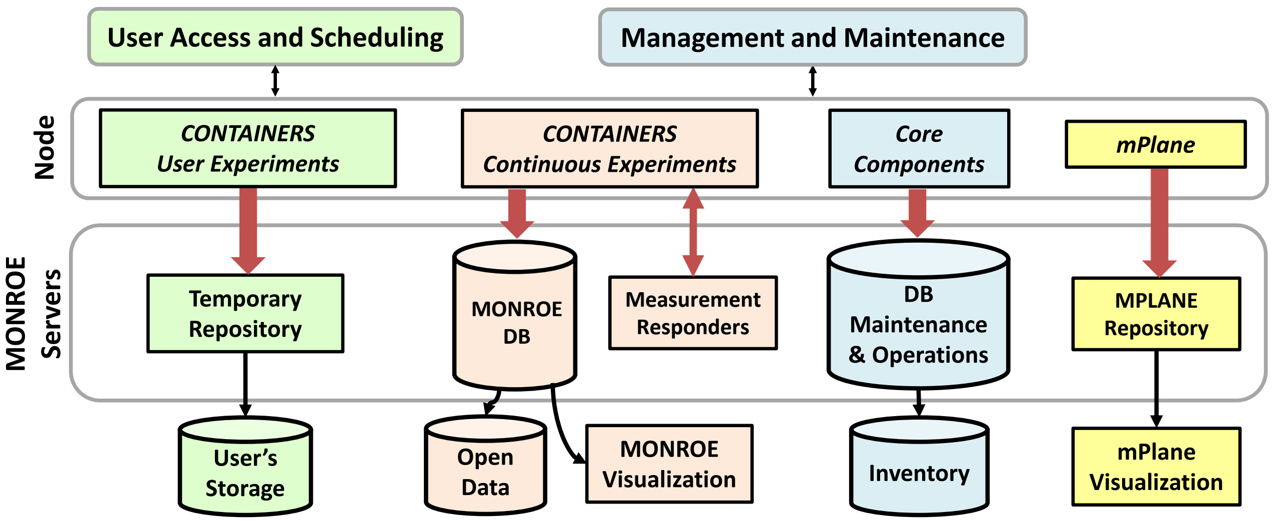


Figure 1: Design of the MONROE system.

During the last two years, the design of the MONROE platform has undergone several major changes to solve various hardware and software issues. Some of the major obstacles we have experienced were:

- **Forced MiFi firmware updates:** In the last quarter of 2016, ZTE issued a forced update to the firmware of all MiFis. The update was applied even if the devices were configured not to receive automatic updates. After that, all our MiFis became inaccessible for the MONROE system. The possibility of new forced updates that can completely black out the MONROE platform is not acceptable.
- **Repeated Yepkit USB hub restarts:** During the first months of operation, we experienced repeated apparently random resets of the Yepkit hub. Even more problematic, after several of those events, the

MiFis hang. In some cases, the only way to recover them is draining their batteries, or perform a (labour dependent) manual reboot by pushing the power button.

- **Unstable MiFis:** The modems themselves seem to be prone to resets or to enter a working state (transparent PPP) from which they can only be brought back into normal operation by draining their batteries or performing a manual reboot.
- **Bloated MiFi batteries:** After a few months of work, some of the MiFis showed clear signs of bloated batteries. This problem creates serious safety concerns for the deployment of nodes at places other than our own (controlled) premises.

The above described obstacles suggested the strong need to modify the platform design, particularly to avoid clear safety risks.

Re-design of the MONROE nodes The prototype MONROE node design was consisted of a PC Engines APU1D4, a Yepkit self-powered USB hub, three USB-based CAT4 MF910 MiFis from ZTE, one miniPCI express WiFi card and one miniPCI express (USB-protocol) Sierra Wireless MC7403 modem. The new node design, considering all the above mentioned problems, is based on a dual PC Engines APU2 system. One of the APU2 in each node has two Sierra Wireless MC7455 miniPCI express (USB 3.0) modems; the other has one MC7455 miniPCI express modem and a WiFi miniPCI express card. Table 1 summarizes the evolution of the main platform from the prototype phase to the current state.

Table 1: Evolution of the main platform from the initial prototype to the implementation at M24.

Design aspect	**Prototype**	**Final release (New Node)**
Node platform	APU1D4	APU2
Node configuration	3xMiFis + WiFi	3xMC7455 + WiFi
Node HW	1xAPU + Hub + 3xMiFis + WiFi	2xAPU + 3xMC7455 + WiFi
Management Interface	Yes	No
Operating system	Debian 8 Jessie	Debian 9 Stretch
Modem Type	ZTE MF910 CAT4 USB MiFi	Sierra MC7455 CAT6 miniPCI express modem
Operator naming	usb*N*	op*N*
Network interface naming scope	Up to next event	Whole execution
Interface NAT	MiFi-provided	Node OS-provided

The new node design not only overcomes the safety risks and instabilities, but also presents additional advantages. The benefits of the new design can be summarized as:

1. LiPo batteries are removed from the design, eliminating any safety concerns raised by them and the burden of draining batteries after modem crashes.
2. The USB hub is removed, eliminating related instability issues.
3. When replacing the MiFi modems, LTE Category 6 ("CAT6") miniPCI express modems from Sierra Wireless have become available. The original Sierra Wireless modems used for management were LTE Category 3 ("CAT3"); the ZTE MiFis used initially were only LTE Category 4 ("CAT4"). Therefore, replacing Mifi modems also allowed us to upgrade the MONROE platform to follow industry deployments.

4. Sierra modems are simpler devices than the ZTE MiFis (which were full Android systems); that will reduce overheads in the chain from the MONROE node protocol stacks to the MBB network.

5. The prototype platform used the NAT mechanism provided by the ZTE MF910 MiFis. As the second iteration of the platform design uses only miniPCI express Sierra Wireless modems without NAT, this functionality has been moved to the operating system itself, where it can be controlled and configured by the MONROE platform.

6. The prototype exposed the network interfaces of the nodes to the experiments running in the containers using names in the form usb*N* (usb0, usb1, ...). The association between an interface name and the MiFi/SIM/operator connected to it could change after events such as modem disconnection, even during an experiment execution. That forced experiments to read the new operator association for each interface from the metadata stream before selecting the interface they were binding to after any networking events. In contrast, the final implementation uses a naming schema where interface names in the form of op*N* (op0, op1, ...) associate the interface with a given modem. This association persists through the entire uptime of the node, and is only reset at bootup. Therefore, experiments need to wait for metadata information only once, simplifying their design.

One drawback of the new design is that due to unavailability of the fifth interface, the new node comes without a dedicated management interface. This requires modifications to the core components to enable the transfer of metadata and experiment results through the other modems where they are free from experiment traffic.

Finally, it is worth to mention that despite the above described obstacles, the MONROE project was able to continuously operate a sufficient number of nodes, and provide service to the participant projects of the first Open Call.

The following sections provide an overview of different components of the MONROE platform focusing on the details of the design and the final implementation.

2 SW in the MONROE nodes

The software in the MONROE nodes is based on a Linux Debian *Stretch* distribution. On top of the operating system, several core components keep the node in a healthy and updated state. Experiment code runs inside Docker containers, which offer lightweight virtualization and a convenient, efficient, way of software distribution.

In general, core components perform low-level work more or less in line with the normal work expected on any mobile device or computer (e.g., device and network management, service watchdogs). For user experiments, the software ecosystem composed of the scheduling system, background experiments and experiment services is more important, as experimenters should be aware of any potential interferences with their own experiments.

2.1 Core components

The core components of the MONROE node ensure that the node remains operational and enable remote update of all the other software components. The main ones, shown in Figure 2, are:

- **System-wide Watchdog:** Responsible for ensuring that all core services are running. In case of anomalies, it restarts the affected services.

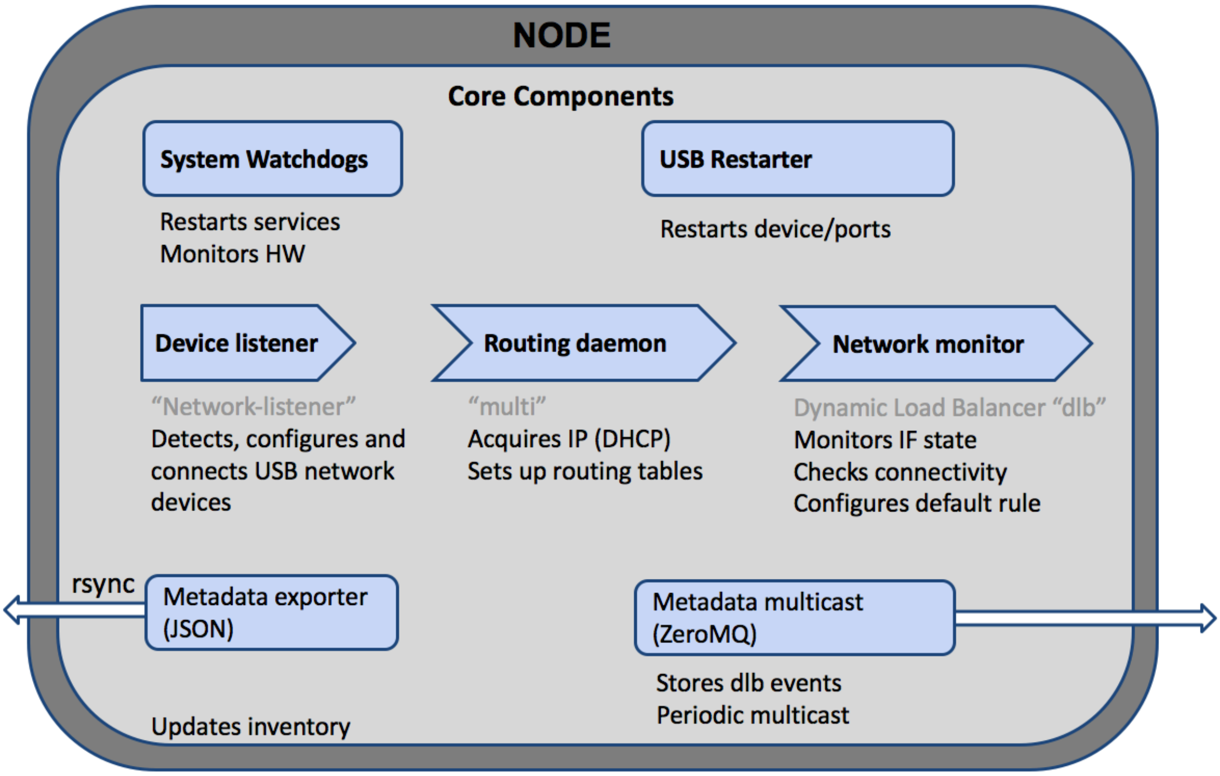


Figure 2: Core components in the MONROE nodes.

- **USB restarter**: Restarts or power-cycles USB devices.
- **Device Listener ("network-listener"):** Detects, configures and connects USB network devices.
- **Routing daemon ("multi"):** Acquires an IP address through DHCP, sets up routing tables (only IPv4).
- **Network monitor:** Based on the Dynamic Load Balancer ("dlb"). Monitors interface state. Checks the connectivity of the different interfaces. Configures default routes.
- **Metadata multicast & exporter:** Broadcasts the stream of metadata (e.g., node status, connection technology, GPS) as JSON objects to all the applications in the node using a publish-subscriber paradigm based on ZeroMQ.[1] Different experiments can subscribe to specific relevant information, for example to correlate GPS/operator with a throughput measurement. The metadata is also collected, transferred to the MONROE server and stored in the MONROE (Cassandra) database for post-processing and correlation with experiments.

2.2 Containers

Both default MONROE experiments and user experiments are executed inside Docker containers, which provide resource isolation from the host node. Docker containers are based on a layered file system, where a container can reuse layers shared with other containers. MONROE provides a default base image for the experiment containers under the name `monroe/base`. This base image provides a base operating system

[1] http://www.zeromq.org

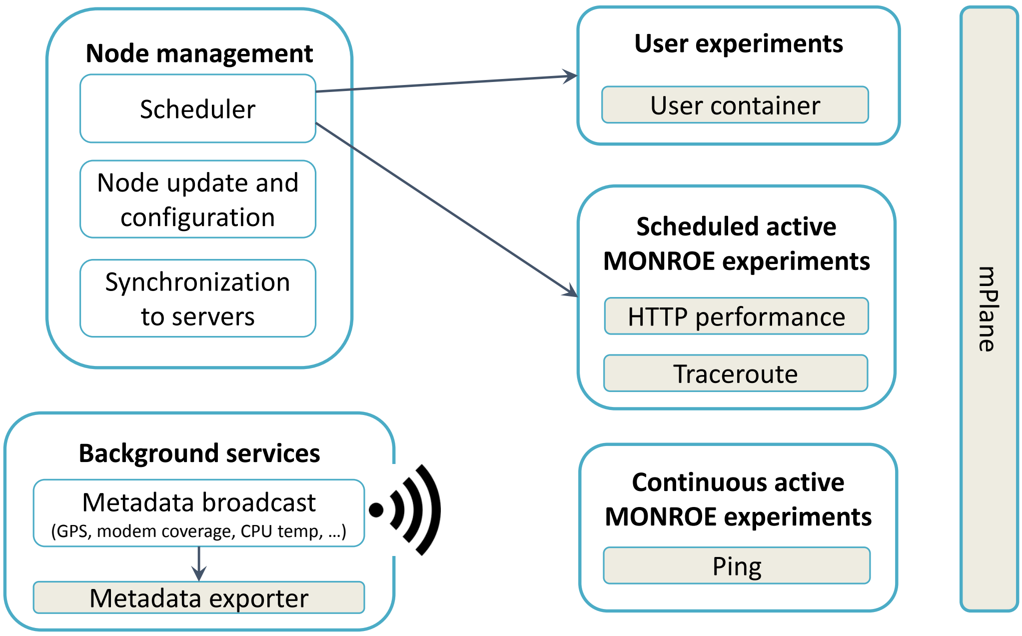


Figure 3: SW ecosystem in the MONROE nodes.

installation with default tools that are potentially useful for many experiments. When users base their own containers on the MONROE base image, they get automatic access to its underlying contents. This is a relevant consideration because it allows lightweight containers to provide just the contents that are unique for the particular experiment, significantly reducing the download and deployment time and traffic volume. As the base image resides permanently in the nodes, nodes need to transfer only the new layers created by the users for their experiments, saving data quota usage on our SIM subscriptions and hence, leaving more quota to run experiments. Our public software repositories contain all the files necessary to build new user experiments.

Experiments running inside a container have access to the experimental network interfaces. They can read and write on their own file system, overlaid over that of the base MONROE image. They can use any software tool installed in the base image, or they can install their own tools and libraries in the overlaid file system. Finally, there are specific paths (e.g., `/monroe/results/`) where the experiments can write their results; the node will automatically transfer them to the MONROE servers.

2.3 SW ecosystem in the MONROE nodes

Figure 3 presents the different software elements that coexist in a MONROE node. In the first place, the node management software runs continuously in the background. It includes the scheduling system, which periodically checks for new experiments to run in the node and deploys these in advance to their scheduled execution time. It schedules the start and stop times of the container using operating system functions. During experiment execution, it also checks if the current one has exceeded its allocated resource quotas. Synchronization of experiment results and metadata (JSON) files is performed by a background `rsync` process. Node package and configuration updates are at charge of an `ansible` process. Second, some services such as metadata broadcasting run continuously on the background. The impact of those services on node performance is negligible for most experiments.

MONROE nodes continuously run some default experiments. Currently, this is limited to the `ping` ex-

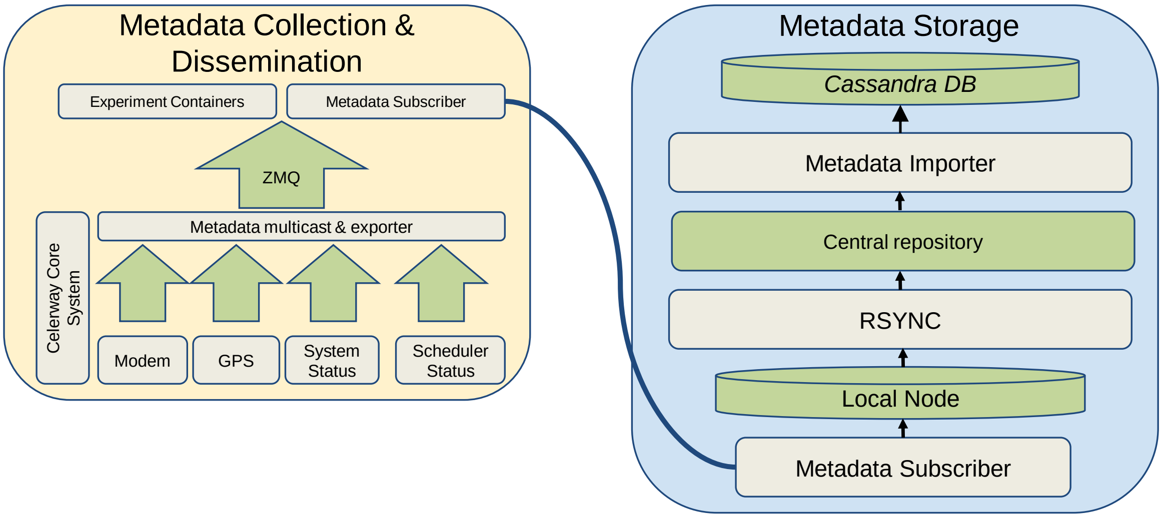


Figure 4: Flow of metadata in the MONROE nodes.

periment, which sends an ICMP PING probe every second through each interface. Experimenters should be aware of any impact that this condition might have on their own experiments. Similarly, certain MONROE base experiments such as `http_download` and `traceroute` are executed in the node. However, those experiments, which are more resource and bandwidth intensive, are scheduled periodically in exclusion with any other experiment, including user ones. Thus, users may be unable to run their experiment at a certain time on a certain node because one of the base experiments is already scheduled, but, once the scheduling of a user experiment is approved, it will not be executed at the same time than the scheduled active MONROE experiments. User experiments execute, inside their Docker containers, in the node under the supervision of the scheduler. Finally, the mPlane Tstat probe runs continuously in all MONROE nodes to supervise all the network events in the platform.

2.4 Metadata creation and flow in the nodes

Figure 4 shows the flow of metadata inside the MONROE nodes. Different subsystems generate metadata messages, which are received by the metadata exporter. The exporter formats the information from different sources as JSON single-line objects. ZeroMQ is used to create a publisher/subscriber model, where the metadata exporter acts as publisher and any other piece of software, including user experiments, may become subscribers. The receiving mechanism is based on a ZeroMQ TCP socket abstraction.

A special MONROE module, the metadata subscriber, receives all metadata messages and writes them to a predefined location in the node file system (`/monroe/results/xxx.json`). `rsync` is used to transfer the JSON files to the MONROE server over a secure SSH channel. At the server, the files are parsed and imported into the Cassandra database. Finally, JSON files are backed up daily and automatically copied to a second machine at IMDEA Networks. An additional backup of that machine is made at IMDEA discretionarily.

Individual metadata messages are labeled by topic. Applications can subscribe only to specific topics, or to the whole stream. The format of the individual metadata messages is detailed in the user manual.

2.5 Tstat & mPlane in the MONROE nodes

Here, the most important features of the mPlane and Tstat architecture are summarized.

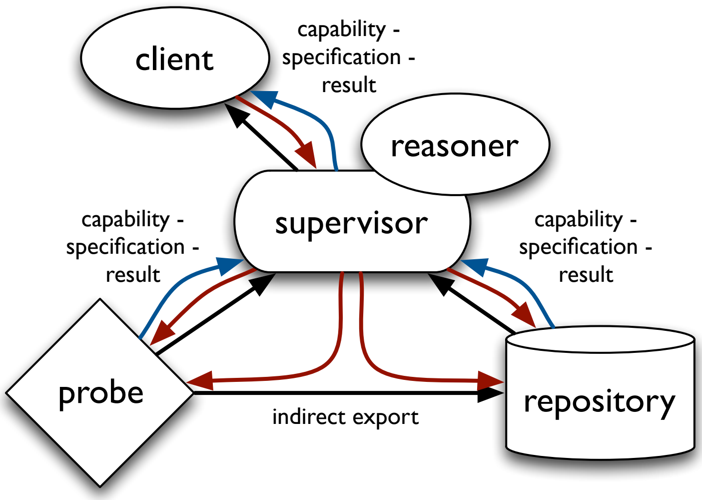


Figure 5: The mPlane architecture.

2.5.1 mPlane architecture

Figure 5 summarizes the mPlane architecture. An mPlane infrastructure consists of a set of components meant to perform passive or active measurements, or to store and analyze the resulting data. Components can be roughly divided into probes and repositories. Probes perform raw measurements, and may preprocess them. Repositories store, correlate and analyze the measurements provided by multiple probes. These components are coordinated by a supervisor, which handles the mechanics of distributed measurement (e.g., component discovery, capabilities management, access control) and final analysis, correlation, and compilation of results from multiple repositories and probes.

Interaction in mPlane begins from a set of component capabilities: On the one hand, a supervisor collects the capabilities of the components it supervises, and presents capabilities to clients (e.g., representing measurements it can perform or queries it can answer with its components); on the other hand, a client selects a set of capabilities and sends a specification to the supervisor, i.e., a description of which measurement to perform, how, where, and when. The supervisor authenticates the client, checks its authorization to perform the measurements called for in the specification, and sends corresponding specifications to the appropriate components. Results returned contain all the parameters of the specification used to generate it, so that they are self-contained. This simplifies management in large-scale deployments, while reducing the amount of state that each component has to store while waiting for one of its specification to return.

2.5.2 mPlane integration in the MONROE platform

To offer a service that may be useful for MONROE users in general, each node is instrumented with mPlane and the Tstat passive probe; thus, MONROE nodes are able to extract measurements and present them to any interested user. Measurements produced by each node are then collected in our repositories.

The Tstat[2] probe runs on all nodes in the mPlane container as one of the basic MONROE containers. The Tstat is a passive probe that provides insights on the traffic patterns at both the network and the transport levels. The Tstat generates two different types of logs.

[2] http://www.tstat.polito.it/

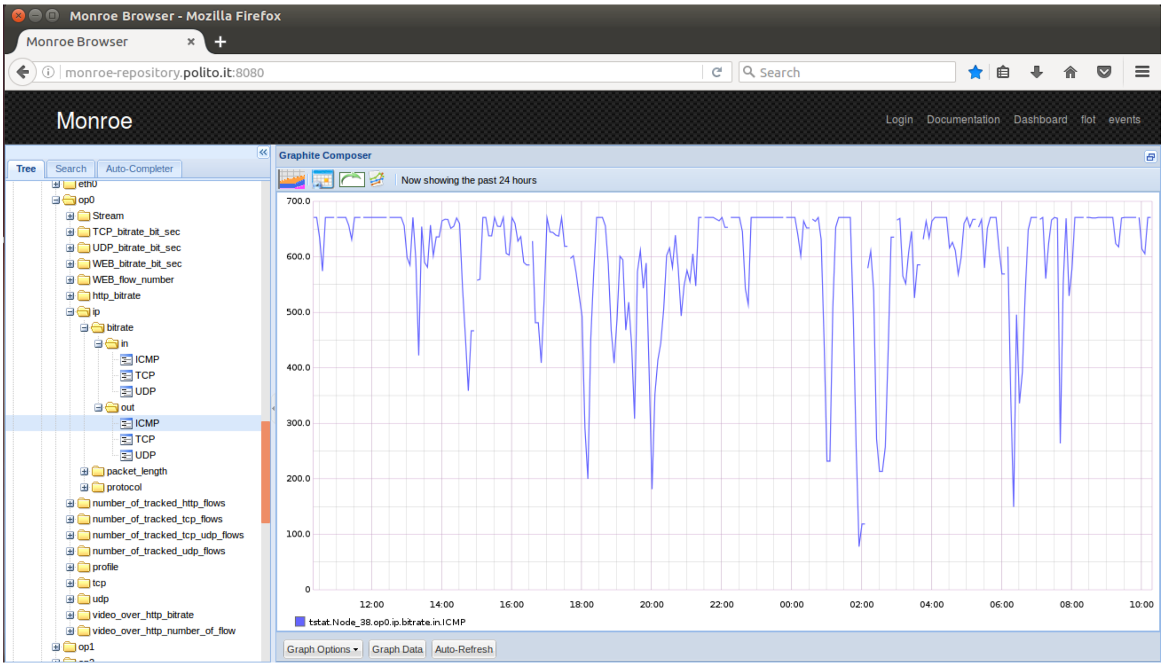


Figure 6: Graphite GUI of the Tstat RRD logs.

2.5.3 Tstat Round Robin Database

The RRD (Round Robin Database) log is an average of samples of each packet during the last 5 min. The detailed description of the RRD logs is available on the Tstat documentation[3]. RRDs are available at: http://monroe-repository.polito.it:8080/

The Graphite GUI provides a tool to present RRD logs and save interesting plots. For example, Fig. 6 shows the bit rate of ICMP packets for node 38 on interface `op0` over the last 24 h. There is also the possibility to create a dashboard to monitor the experiments and interfaces' status. Fig. 7 illustrates an example of saved dashboard to monitor the volume of traffic on one node.

2.5.4 Tstat logs

Tstat generates detailed flow-level logs for TCP, UDP, and HTTP flows. These are text file with more than 100 metrics, with information on client and server addresses, network and application level metrics, and DNS queries. The description of the metrics can be read at: http://tstat.polito.it/measure.shtml#LOG. In MONROE, Tstat is configured to generate four different logs:

- log_tcp_complete: Every TCP connection that has been tracked
- log_tcp_nocomplete: All the connections for which the three-way handshake is not properly seen
- log_udp_complete: Every tracked UDP flow pair
- log_http_complete: Information from every HTTP request and response

Logs are available in two ways:

[3] http://tstat.polito.it/HOWTO.shtml#RRD

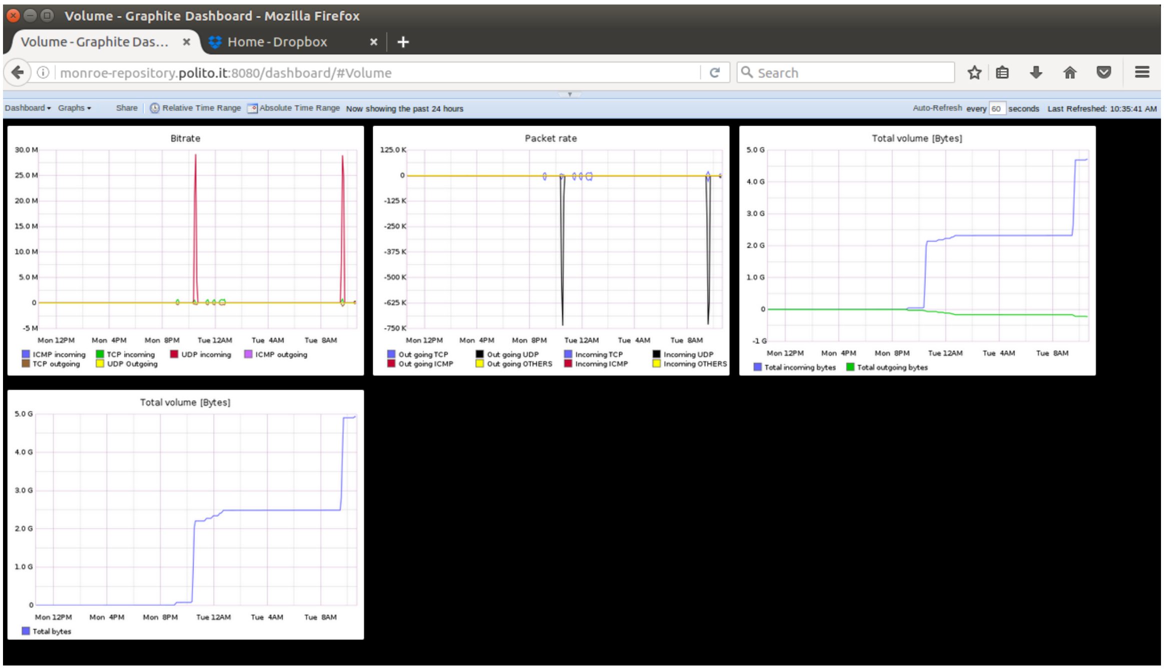


Figure 7: An example dashboard on Tstat RRD GUI.

1. Real time access on the nodes. The last three generated logs are shared with MONROE experimenters at `/monroe/tstat`. Thus, MONROE users can use passive traces collected by Tstat during their experiment. The three logs can cover at most the last three hours.

2. On demand. Logs from all nodes are imported into the MONROE database. The table schemas are available in the MONROE repository at: https://github.com/MONROE-PROJECT/Database/blob/master/db_schema.cql. The columns (NodeId,Iccid,DataId) allow joining entries in those tables with the rest of metadata.

The complete description of the logs is available at: http://tstat.polito.it/measure.shtml#LOG

3 Node management and maintenance

The operations team uses several mechanisms to monitor node status and ensure that they remain operational with minimum manual intervention. It is based on a combination of software running both in the nodes and in the maintenance servers, which are operated by Celerway. Additionally, a ticketing system for maintenance issues has been created to allow identifying repeated maintenance actions that should be incorporated into maintenance routines. The following sections describe the different mechanisms involved in the process of node maintenance.[4]

3.1 Configuration maintenance

Monroe node configuration is managed and synchronized through an automatic configuration management system (ansible). In regular intervals, a private git repository is checked out and the configuration updates applied to the node. No action is taken unless a task is updated. Updates to the packages installed

[4]Part of the information in this section is explained in deeper detail in Deliverable 4.1.

and node configuration are handled exclusively through the ansible system. Site-specific variables, such as WiFi configuration, can be set in an imported file on the node.

3.2 Health monitoring

The software environment in the MONROE nodes consists of several layers, all of which must be operational to make the node available for experimenters, and to ensure the correctness of the measurement results. The following is a list of the different software components that run on the nodes:

- Maintenance access.
- Software watchdog.
- Kernel patches.
- Core software (routing, load balancer, network-listener).
- Sensors.
- Metadata-exporter.
- MONROE base experiments.
- Usage monitoring.
- Scheduling client.
- Container and virtualization system.

Some of the mechanisms implemented that monitor the status of the nodes are as follows:

- **Network assessment:** Low data throughput checks are run every 5 min in order to assess all different interfaces. The management interface is the default for all maintenance activities; however, if it is not available due to a problem or lack of coverage, the node will switch to the MiFi interface with the best quality, hence maximizing the likelihood that maintenance activities can be carried out.

- **Hardware watchdogs for rebooting the node:** The hardware watchdog triggers a reboot if the system becomes unresponsive, e.g., in the case of a kernel failure. The watchdog checks if a device file has been written to at least once. If this is the case, but no subsequent writes occur within a defined period, a reboot is triggered. A software daemon in the node writes to the device inside the defined interval, preventing node reboots. Thus, the node will reboot only in the case of severe system corruption.

- **Software watchdogs for rebooting the node:** The daemon[5] that writes to the watchdog device can run the tools that define a test procedure; it also has a repair procedure to run if the test fails. Should a repair action fail, the watchdog will trigger a reboot. This watchdog is designed for monitoring system level operations; more complex tests are handled by the MONROE watchdog.

- **MONROE watchdog:** High level watchdog that runs at regular intervals to monitor all necessary services. This watchdog can implement more complex tests, repair actions, and resolutions. In particular, it can move the node to *maintenance mode* (below), trigger a reboot, or initiate a complete reinstallation of the base system through the BootOS. Only if the tests defined in this watchdog succeed, a successful boot flag is written. In particular, repeated failures to boot the node into a working state will eventually trigger a reinstallation of the system by the BootOS.

- **Maintenance mode:** When the node is up, but configuration errors are observed or certain tests fail, the node goes into maintenance mode. In this mode, all Docker containers are stopped immediately

[5] http://linux.die.net/man/8/watchdog

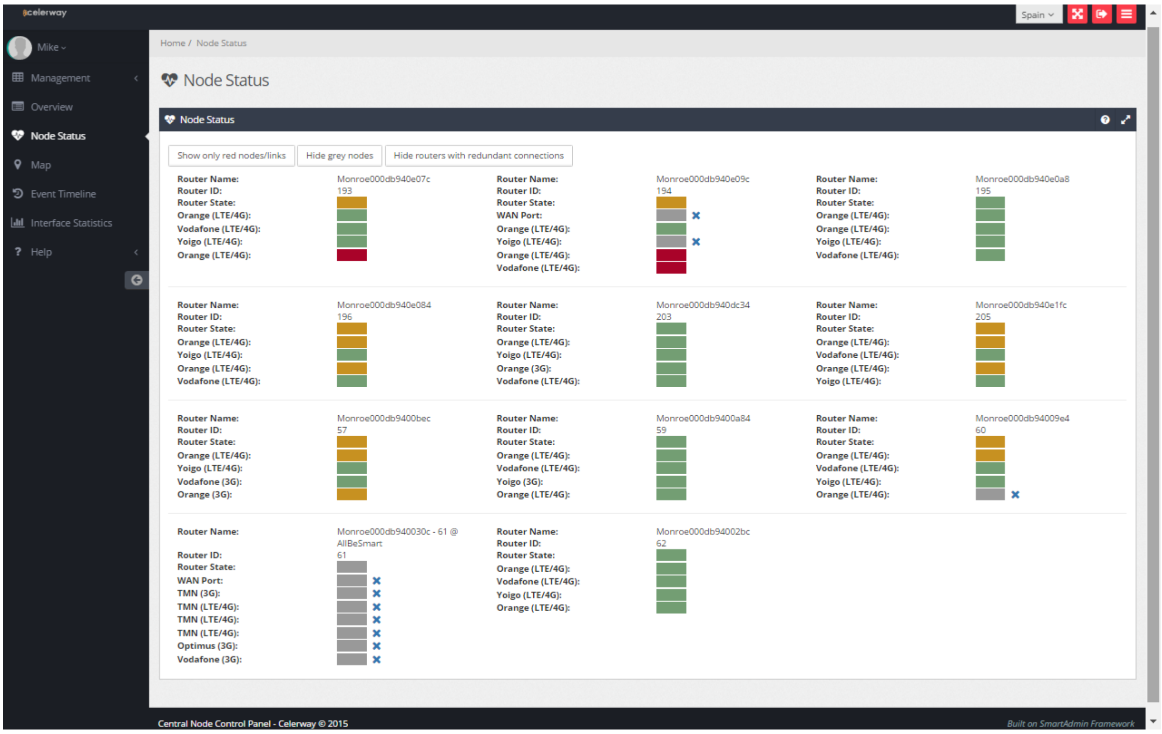


Figure 8: Screenshot of the node inventory developed by Celerway for MONROE where the status of the nodes in Spain can be monitored.

and a message is written to syslog (every minute). Additionally, the node status is set to maintenance in the scheduler, disallowing new experiments. An email is sent to the maintainer of the node to initiate troubleshooting procedures. Maintenance mode has to be manually reversed by the engineering team once the issue is resolved.

3.3 Node inventory

Celerway's inventory system allows monitoring the status of all the nodes in the MONROE platform. Figure 8 shows how the MONROE maintainers can quickly check the status of all the nodes in their site.

The inventory system is organized around a database that stores the status information sent continuously by the nodes. For example, each node sends periodically a "heartbeat" message to the inventory to signal that it remains active. The nodes report also the status of each of their network connections, including the management interfaces (in the first design iteration), Ethernet and WiFi interfaces.

In addition to monitor the status of the nodes, site maintainers can use the inventory web interface to change the configuration of the nodes. For example, the status of a node can be defined as "testing," "deployed," "storage" or as part of private projects not used in MONROE.

3.4 Manual remote inspection

In order to ease the process of problem diagnosis, particularly during the early phases of the platform deployment, Celerway enabled an access mechanism to the nodes based on reverse SSH tunnels. MONROE maintainers can use their private SSH key to access Celerway server and then connect to any nodes at their sites. As an example, commands such `lsusb`, `ifconfig`, or any of the MONROE tools for MiFi monitoring (`mf910-*`) can be executed at the nodes. Site maintainers may also reboot nodes to try to fix hardware issues, if appropriate.

This access mechanism is strictly reserved for MONROE maintainers. Users of the platform (experimenters) cannot use the reverse tunnel mechanism, as it enables access to the nodes outside the virtualized environment provided by containers.

3.5 Node recovery

This section briefs the procedures designed to enable a hard restart and bring automatically the system back to a known working state.[6]

The various watchdogs in the nodes check for critical conditions. When triggered, they set a flag signaling the severity of the issues found. Errors resulting in a reinstall flag being set are resolved by a reinstallation of the node from the BootOS. This method can recover a node both from file system errors that prevent system boot-up (e.g., because of frequent sudden power loses in mobile nodes), and also due to software configurations that lead to loss of connectivity.

The nodes have a two-stage boot loader process. In the first stage, the BootOS, which is kept entirely in RAM and only uses read-only hard-drive access for its normal operation, is started. The BootOS uses a standard Linux kernel with the same version used in the MainOS. Upon start, the BootOS verifies that the filesystem of the node is not corrupt, and that no forced reinstallation has been requested. The MainOS partition is mounted and that installation is chain-loaded via `kexec`, performing an in-memory replacement of the currently executing kernel and starting the new kernel. The MainOS is then booted, which contains the MONROE system software.

If the filesystem is corrupt and cannot be automatically repaired, or if a forced reinstallation is requested, the BootOS reinstalls the system from a known working installation image. This is using a simple reinstallation strategy, where a filesystem archive is unpacked onto a newly formatted filesystem, which is very efficent (completes in five minutes) and gives consistent installations.

The BootOS has a communication channel with the MainOS, implemented as a file in the filesystem (`/.bootos`). This file contains a boot counter (incremented by the BootOS in each boot and zeroed by the MainOS watchdog after each successful restart) and a boolean flag that the MainOS can use to forcefully trigger a reinstallation. If the boot counter reaches a configurable threshold, it means that the MainOS watchdog has been unable to run successfully, for whatever reason, and bootos then performs a clean reinstallation to bring the node back into a known working state.

4 User access and scheduling system

User access to the experimental platform is provided via a web interface that enables users to schedule and run new experiments, monitor their status and collect results. The user interface also enables monitoring of the node status and location. Finally, the interface shows the remaining quotas and history for each user.

The user interface is divided in two parts. First, web content is written using a combination of HTML and AngularJS (Javascript) modules with Bootstrap support. Second, the scheduling system is a Python application that uses SQLite 3 for data storage. Nginx is the server used to serve the web content and to act as a proxy for the scheduler.

[6]Further information is provided in Deliverable 2.3.

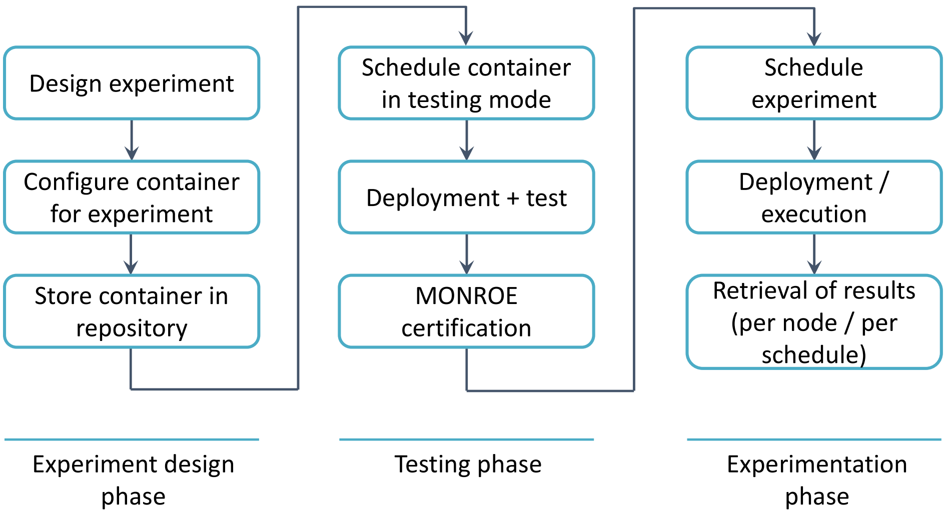


Figure 9: Experimental workflow.

In addition to the web interface, users may develop their own scripts to access directly the REST API exposed by the scheduler through our Nginx server. We are developing a reference script to illustrate direct access to the REST API.

The user interface employs SSL certificates to authenticate MONROE servers and the users. The server certificate is issued by Let's Encrypt.[7] User certificates are issued by iMinds and are compatible with the Fed4Fire platform. The user manual explains how to obtain and install user certificates.

4.1 Development cycle

Experiments conducted in the MONROE platform follow the workflow shown in Figure 9. They consist of three phases: Experiment design, testing and experimentation. During the experiment design phase, the experiment goals and properties are defined and the container required to deploy it in MONROE nodes is configured. During the testing phase, the container is executed on nodes specifically devoted to testing new experiments. If the experiment passes all the safety and behavior tests, a MONROE manager will digitally sign the container image. Signed containers cannot be further modified without running again through the testing phase. Finally, the experimenter is free to schedule the experiment container on any nodes, subject to the specific quotas assigned to their project.

During the phase of debugging or test of user experiments, it may be useful to log in directly to the nodes to run tools from the command line or debug processes during execution. The user interface allows asking for an SSH connection to the container during execution. For this, the experimenter has to provide a public SSH key to the scheduler. Once the experiment is running, the user interface will show complete connection string that can be employed to connect to the running container in the node. For security reasons, this is the only occasion when direct SSH access to the nodes is allowed, and can be used only during the development phase on testing nodes. Deployed nodes do not allow SSH connections to the containers. An example of connection string is:

```
ssh -o StrictHostKeyChecking=no -o UserKnownHostsFile=/dev/null -i your_private_key
    -p 30299 root@tunnel.monroe-system.eu
```

[7] https://letsencrypt.org/

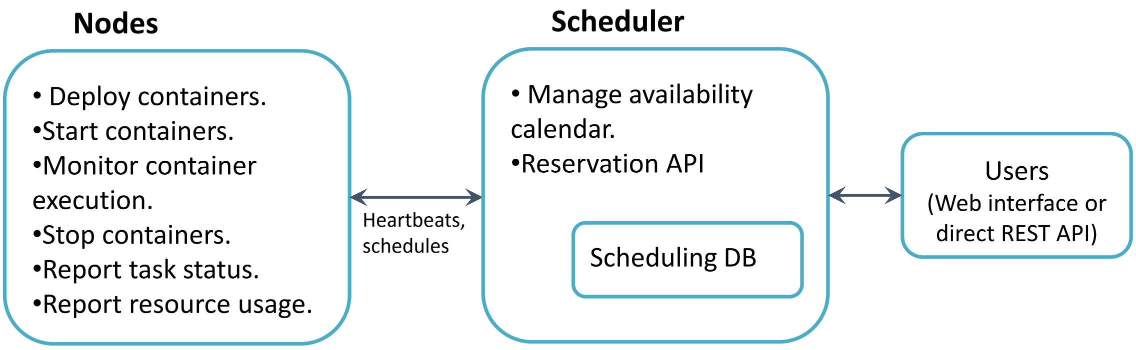


Figure 10: Structure of the scheduling system. The scheduling database is implemented with SQLite 3 and runs in the MONROE server.

4.2 Scheduling system

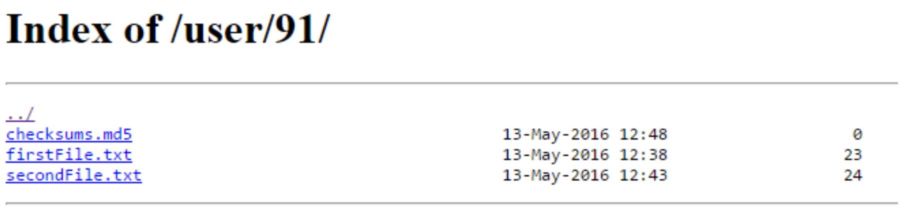
The scheduling system allows experiment execution guaranteeing no conflicts between them. Figure 10 shows the overall structure of the scheduling system.

The scheduling system is split in two parts. The scheduling server runs on a MONROE server behind an Nginx proxy. It uses an SQLite 3 database to store user roles, node and experiment status, and schedules. It offers a REST API that can be accessed through the web user interface or directly through the Nginx proxy if users develop their own access scripts. The client part of the scheduler runs on each MONROE node. It periodically contacts the scheduler in the server to send “heartbeats” and traffic statistics, and check for new schedules for the node. Due to connectivity constraints, particularly in mobile nodes, deployment of experiments to the nodes is pre-empted relative to the scheduled execution times. When new schedules are available, the scheduler preloads up to three containers, depending on criteria such as available storage in the node and time until schedule. It also schedules the start and stop times of each container using operating system functions. When the time to execute a new container arrives, the operating system executes the container using the Docker tools. Finally, the scheduler monitors the experiments to check if they exceed the allocated resources and to transfer any result files and inform of result codes.

4.2.1 Scheduling policies

The following policies are currently respected for the scheduling of experiments:

- Experiment scheduling is based on time slots. Each experiment may request one fixed time slot in the range of 5 min to 24 h.
- Priority is on a first-come, first-served basis, but user quotas are enforced to ensure fairness in the use of available resources (currently, data quotas for the MBB subscriptions and execution time).
- Normal user experiments are executed in isolation (except for continuous background MONROE experiments such as `ping`). However, an experiment may define itself as “shared,” meaning that it will allow execution of other experiments that also define the same flag. *Normal experiments do not share execution and thus will not be executed concurrently with others, even if those declare themselves as “shared.”*
- The scheduler supports the definition of periodic experiments. The minimum repetition period is 1 h; the maximum length for a periodic schedule is 1 month. Thus, for example, an experiment may execute every day at noon for half an hour during two weeks. A periodic schedule is treated as atomic, i.e., all slots will be allocated or none will be.


Index of /user/91/

../		
checksums.md5	13-May-2016 12:48	0
firstFile.txt	13-May-2016 12:38	23
secondFile.txt	13-May-2016 12:43	24

Figure 11: Folder containing the results of an individual schedule, transferred to MONROE's servers.

- Experiments can be scheduled over several nodes concurrently (for any given requested period, periodic or not). Schedules over several nodes are treated as atomic, i.e., if not all nodes are available for the requested time slots, the whole schedule will be refused.
- Nodes may be of different types: Testing or deployed; static or mobile. They can be placed at different countries and sites (e.g., Norway, Sweden, Spain). Scheduling requests can specify or reject any type of node using filters, or simply accept any available node selected automatically by the scheduler.

4.3 Transfer of user experiment results

Any files written during the experiment to the `/monroe/results/` directory will be synchronized to the experiment repository. This operation happens continuously during experiment execution and then upon its finalization.

The folder contains, in addition to the files generated by the experiment, log files detailing the deployment, startup and stop phases of the container execution.

The result files and log files can be accessed through the user interface: For experiments that have already been started, the interface presents a link under the column "Results" that redirects the user to the HTTP folder (Figure 11) that contains the files already synchronized from the node where the experiment runs to the repository. In this way, the experimenter can retrieve result files even for partial experiments that fail or are canceled.

In addition, the experiment may use any network functionalities to communicate with outside servers as needed (e.g., `scp` some files to an external server). In order to improve safety, private keys should be restricted to the experiments and discarded after a reasonable time. Additionally, instead of saving keys in the container itself, users may want to pass them as additional options during experiment scheduling. The values will be available during container execution as a JSON file at `/monroe/config`. This file is created by the node scheduler. The same effect is achievable when the containers are run manually in user development nodes adding the `-v` option to the command line. To map both a locally created `config` file and the results folder of the container to a node folder, in development nodes without a scheduler, the following command line options may be used:

```
docker run ... -v /monroe/results:/monroe/results
               -v /monroe/config:/monroe/config:ro ...
```

5 Remote repositories and databases

The results of the passive metadata measurements and of the continuous background experiments (e.g., ping) are collected in the nodes in JSON format and transferred to the MONROE servers using `rsync` over a secure SSH channel. Once at the server, the metadata-importer processes the JSON files and inserts their

contents into the Cassandra database. Each metadata topic and MONROE experiment has its own database table. The schema of all the tables can be checked at:
https://github.com/MONROE-PROJECT/Database/ (file `db_schema.cql`).

5.1 Database

MONROE database is based on a NoSQL system, Apache Cassandra version 3.4.[8] The database follows an experiment-oriented design, where user and application queries have a central role in the design. The database is divided into two collections of tables, one for collected metadata and one for the results of default experiments:

- **Metadata tables:**

```
monroe_meta_
            device_gps
            device_modem
            node_event
            node_sensor
```

- **Default experiment tables:**

```
monroe_exp_
           ping
           http_download
           exhaustive_paris
           simple_traceroute
           tstat_http_complete
           tstat_tcp_complete
           tstat_tcp_nocomplete
           tstat_udp_complete
```

The primary database is currently located in a virtual machine hosted in a server at KaU. The metadata-importer runs in the same machine, which is also the destination for the synchronization of the JSON files arriving from the nodes. In this way, network latencies between components are minimized. Figure 12 shows the flow of data between components of the MONROE platform, as explained in the following paragraphs.

5.2 Example scripts and utilities

MONROE public git repositories host a small set of examples for accessing the Cassandra database from Python:

- **dailyCassandra2CSV.py:** This example corresponds to the tool that produces the daily CSV dumps in our database servers.
- **GPS2KML.py:** Given a node number and starting and ending timestamps, this example writes a KML file with the GPS positions of the node during the specified period. The KML file can be imported directly in Google Earth.
- **CoverageGPS.py:** Given a node number and operator name, this example extracts data from the GPS and modem metadata tables between two specified timestamps. The data are then correlated to produce a KML file that shows, for every position, the type of connection and signal quality detected by the modem connected to the specified operator. The files `Mark_*.png` must be present in the same folder than the generated KML file when opening it with Google Earth.

[8] http://cassandra.apache.org/

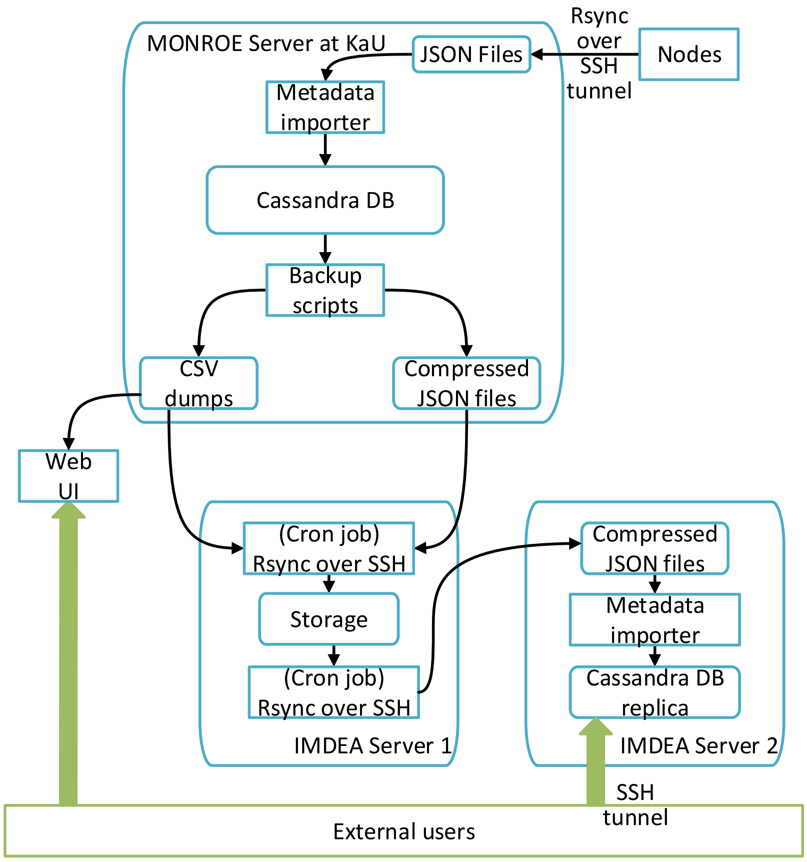


Figure 12: Flow of data between components of the MONROE platform, including backup servers and access points for external users.

5.3 Access to the data

External users can access MONROE metadata and the results of the default experiments in three ways. First, a dump of every table in the Cassandra database is generated in the main database server daily at 07:00 CET. The files are moved to a location that is accessible through the web user interface at 12:00 CET. In this way, users can easily get a daily download of the new contents for all the database tables in the previous day.[9] This process can even be automated, e.g., using `wget` with the certificate that users employ normally to access the user interface. The URL for accessing the daily CSV dumps is:
https://www.monroe-system.eu/user/dailyDumps/

Second, users can access a Cassandra database replica located at IMDEA directly. To avoid that corrupted data from this publicly-accessible replica propagates to the main MONROE database, this replica is not directly connected to the main one. Instead, the compressed JSON files are pushed into that machine by the machine that acts as backup at IMDEA. That is, compressed JSON files are copied by a machine at IMDEA that acts as backup server and this same machine copies them to a different machine at IMDEA that hosts the Cassandra open replica. The process starts everyday at about 09:00 CET (just when the files are copied from the main MONROE servers at KaU). A normal metadata-importer process runs in the replica machine to parse the JSON files and import them into the database, just as it happens in the primary database copy. As it takes some time to process the quite large number of JSON files that the nodes generate every day, data from the previous day is normally available in the replica around noon.

Users access the database replica through an SSH connection. However, the user they use has no permis-

[9]Our automated scripts run on a server that uses CET times, but timestamps from the nodes refer always to UTC time. Thus, users should be aware of changing Winter/Summer calendars when looking for data at sensitive day boundaries.

sion to run a shell in the server. Thus, they can only use the connection to establish a tunnel to a port at their local machines. Afterwards, they are free to write their own scripts that connect to their local port as if they were connected directly to the database replica. Queries executed by the script run in our database replica server, while any post-processing performed by their scripts runs locally in their machines. This helps also to ease the load in our servers.

Finally, all data produced by the MONROE consortium will be published as OpenData periodically in Zenodo repository.

5.4 Backup systems

The JSON files that arrive from the nodes are compressed daily at 03:00 CET to a folder in the database machine. A cron script running in a machine at IMDEA Networks uses rsync over a secure SSH tunnel to copy the compressed files for off-site backup purposes. The backup is performed daily at 09:00 CET. IMDEA personnel produces additional local copies of the backup files discretionarily.

The CSV files containing the daily dumps of the database tables are copied to the same machine at IMDEA every day at 09:00 CET.

6 Visualization tool

Data and metadata stored in the database can be visualized using MONROE's web-based visualization tool. This tool provides a graphical representation of the MONROE platform, including interactive graphs such as time-based performance measurements, connection type/quality tracking and GPS location. As an example, Figure 13 shows the main page of the visualization tool and Figure 14 presents the basic statistics reported for a concrete node in a given 6 h period. Figure 15 details the RTT graph for the ping experiment across all its MBB interfaces.

From an architectural point of view, the visualization tool is composed of two layers:

- **Back-end server:** Connects to the MONROE (Cassandra) database to retrieve node capabilities, device positions and monitoring information. Data is exposed to the upper layer through a REST interface.
- **Front-end client:** Handles web pages and their contents, including third-party libraries that create formatted output (e.g., charts, maps, tables).

The back-end layer is based on `NodeJS` and the *Express* web application framework. The front-end layer is implemented using the `AngularJS` javascript framework.

The visualization tool is publicly accessible from a server hosted by KaU at:
http://visual.monroe-system.eu

7 Conclusions

This document has presented that implementation of the MONROE platform at M24, explaining the modifications introduced to cope with the difficulties encountered during the development phase and the feedback from the first users of the platform. In particular, this document has covered the software architecture of the platform, from the software running in the nodes to the backup scripts in the different servers. Particular interest has been placed on explaining the user interface and scheduling systems, the management and maintenance systems and the metadata visualization tool.

Figure 13: Main page of the MONROE visualization tool showing the location of nodes at the different platform sites.

Figure 14: Basic statistics shown for a node built from data gathered through the MONROE platform metadata database.

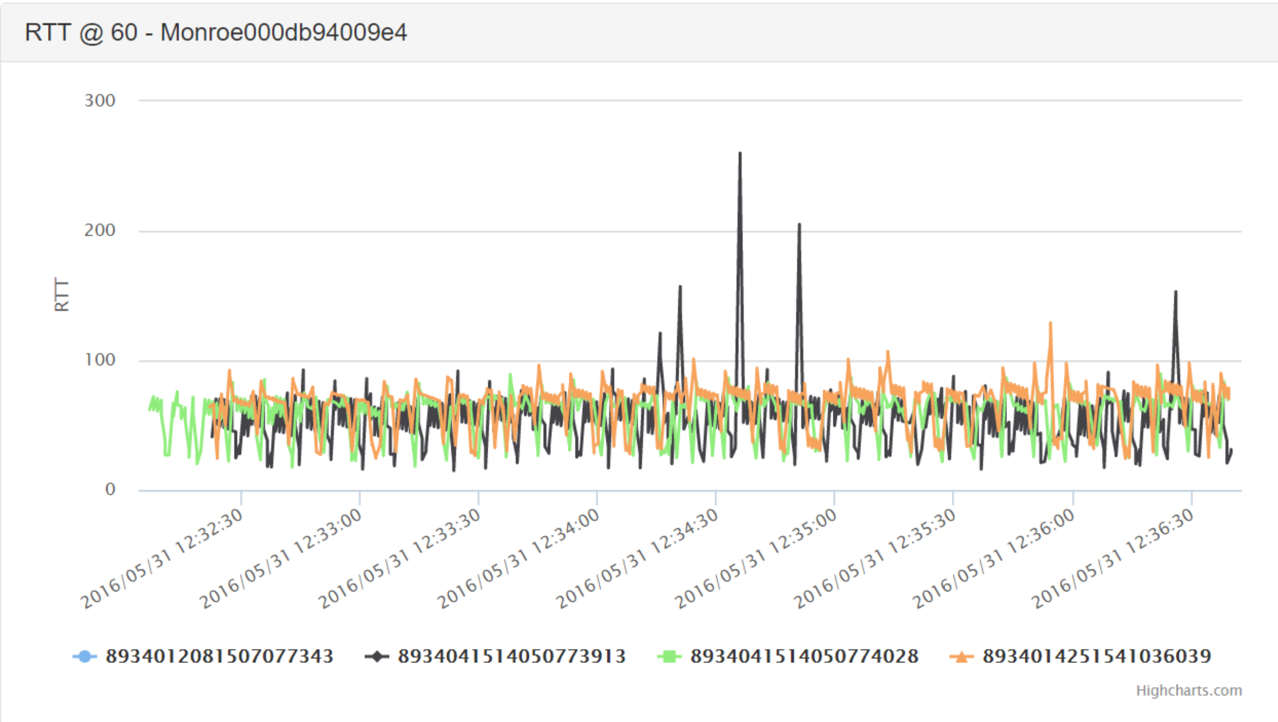


Figure 15: Interactive RTT chart produced by the MONROE visualization tool.