MONROE

Measuring Mobile Broadband Networks in Europe

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Report on Hardware Design and Selection

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Abstract

In this report, we present a detailed description of the hardware design we propose for the MONROE measurement node. We thoroughly describe the equipment requirements we identify and the subsequent selection criteria we implemented. We then present the different alternatives we evaluate for the main blocks of the node and the testing procedures we follow in order to validate the applicability of the node and the components we select. Finally, we discuss the limitations of the hardware and the MONROE node life-cycle.

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

1 Introduction

In this report, we present the hardware design and selection process for the MONROE measurement node. The key goal of the MONROE project is to design, build and operate an open, European-scale, flexible platform to run experiments on operational 3G/4G Mobile Broadband (MBB) networks with WiFi connectivity, and to enable large-scale experiments in such networks. For this, we leverage a considerable amount of experience we gathered from operating the NorNet Edge (NNE) infrastructure of 200 dedicated nodes spread across Norway[1]. However, in MONROE, we further aim to expand the capabilities and the geographic scope of the NNE platform by covering four European countries (Spain, Italy, Sweden and Norway), including mobile nodes operating aboard vehicles. This implies selecting a new generation of hardware that can meet the MONROE goals. We translate these goals and expectations into a set of requirements for the MONROE hardware.

More specifially, to build the set of requirements, we take into consideration different aspects of MONROE, including the diversity in terms of use cases, the environment where the node operates (stationary, mobile), the appeal towards external users and the cost of the equipment. First, based on the MONROE use cases that we have previously identified in Deliverable D1.1, we distinguish the necessary features for each MONROE measurement node. It is, for example, important to not be limited by CPU and memory capabilities in order to run demanding applications. There is also a need for storage of software packages, results and logs. This is particularly important in cases where nodes are without internet connection to the system back-end and results and logs must temporarily be stored on the node. Second, given that we will open the MONROE platform to external users, we need to also account for the flexibility this requires and support complex experiments that also capture a realistic end-user experience. To achieve this, we use equipment provided by the operators in order to measure using the same hardware that a user would be equipped with. This means using different types of USB-based devices (USB modems and MIFIs). Third, one main focus of the MONROE platform is to facilitate experimentation in dynamic scenarios, under realistic mobility conditions. This drives a unique set of additional demands, including increased robustness of the node and support for GPS in order to track routes and mobility patterns. Additionally, we take into consideration the cost of the hardware and target to select the hardware that allows us to achieve the best trade-off between hardware performance, flexibility and cost.

During the hardware design and selection phase we fix the structure of the MONROE measurement node and test various alternatives for the main hardware blocks. We then select the components that allow us to meet the majority of our requirements. We also design a series of tests in order to verify the sturdiness of the hardware in challenging environments involving high temperatures, humidity and strong vibrations.

In what follows, we first give in Section 2 an overview of the main hardware blocks that constitute the final MONROE node and list our vendor selection. As we move forward in this report, we justify our choices and give a more detailed description of the selection process and the different alternatives we have evaluated. In Section 3, we list the set of requirements we identify for the MONROE hardware. With this in mind, we present in Section 4 the different alternatives we evaluated for each node component.

Once we finalized the hardware design and selection, we ran extensive tests on the MONROE node in order to asses its robustness and performance in challenging environments, e.g., for the nodes operating aboard busses in Turin. In order to verify applicability and identify weaknesses in the design, we have tested the node in different environments, including extreme heat or very high humidity. We describe this in Section 5. Finally, in Section 6 we conclude this report and briefly discuss next steps, such as hardware assembly and deployment batches.

[1] http://robustenett.no/map

Table 1: *Main hardware blocks of the MONROE node, cross-referenced to Figure 1.*

Block no.	Component	Description
1	APU1D4[1] system board 4GB mounted in red metal enclosure[4] with 3 LAN, USB and 6 customized antennas holes.	• CPU: AMD G series T40E, 1 GHz dual Bobcat core with 64bit support, 32K data + 32K instruction + 512K L2 cache per core; • DRAM: 4 GB DDR3-1066 DRAM; • 3 Gigabit Ethernet ports; 2 USB 2.0 ports; • 2 internal miniPCI express slots, one with SIM socket; • Power: 12V DC, about 6 to 12W depending on CPU load; • Board size: 152.4 x 152.4mm; • The board also has an SD card reader, which is currently not used by MONROE.
2	Compex WLE600VX 802.11ac/b/g/n Dual-Band mPCIe module[2]	Dual band AC miniPCI express card that can be used in both access point and client mode.
3	Sierra Wireless MC7304 LTE mPCIe module[3]	miniPCI express card we use for maintenance, updates and transfer of results and to read GPS location of the node.
4	SSD M-Sata 16GB MLC Phison[10]	Used to store OS, MONROE SW, experiments, logs, and results. Can be extended to for instance 64GB if necessary.
5	Yepkit YKUSH powered USB hub[5]	The USB powered hub has 3 ports with individual power cycling and supports 2A per downstream port. We use it to support 3 MBB operators on the node, to which we connect with USB devices such as MiFis, USB sticks and smartphones.
6	External T-blade LTE Antenna[6]	We will use 2 LTE antennas that can be mounted on the red enclosure wall.
7	ZTE MF910 MiFi[7]	We use three ZTE MF910 (CAT4 modems) connected to a powered USB hub (block no. 5). The MiFi comes with a USB cable to be connected to the USB hub.
8	WiFi rubber swivel antenna 2.4/5.0GHz[8]	We attach to the node 3 WiFi dual band antennas.
9	Active/Passive GPS antenna[9]	We will use active and passive antennas (dependent of coverage in busses).

Links to full component description:
[1] http://www.pcengines.ch/apu1d4.htm
[2] http://www.pcengines.ch/wle600vx.htm
[3] http://source.sierrawireless.com/devices/mc-series/mc7304/
[4] http://www.pcengines.ch/case1d2redu.htm
[5] https://www.yepkit.com/products/ykush
[6] https://techship.se/products/external-t-blade-lte-antenna/
[7] http://www.ztedevice.com/product/6f7a05c1-7f2a-4c29-8aec-ceb9cf769d69.html
[8] https://techship.se/products/wifi-rubber-swivel-antenna-24ghz-50ghz/
[9] https://techship.se/products/external-gps-antenna/
[10] http://www.pcengines.ch/msata16d.htm

2 Node Design Overview

The node is a very important component in MONROE, which enables the users to deploy complex demanding experiments in various locations and environments. Next, we give an overview of the main hardware blocks we select for the MONROE node. We mention that these blocks are a part of both the stationary and the mobile MONROE measurement nodes. A complete node consists of a base machine/computer/router with necessary accessories like modems, GPS etc. These components are the ones that were found to fulfill the list of requirements we further specify in Section 3 and also behaved well during the stress tests we further describe in Section 5. We summarize in Table 1 the main components for the MONROE node and we cross-reference it with Figure 1, which shows the assembled stationary MONROE node.

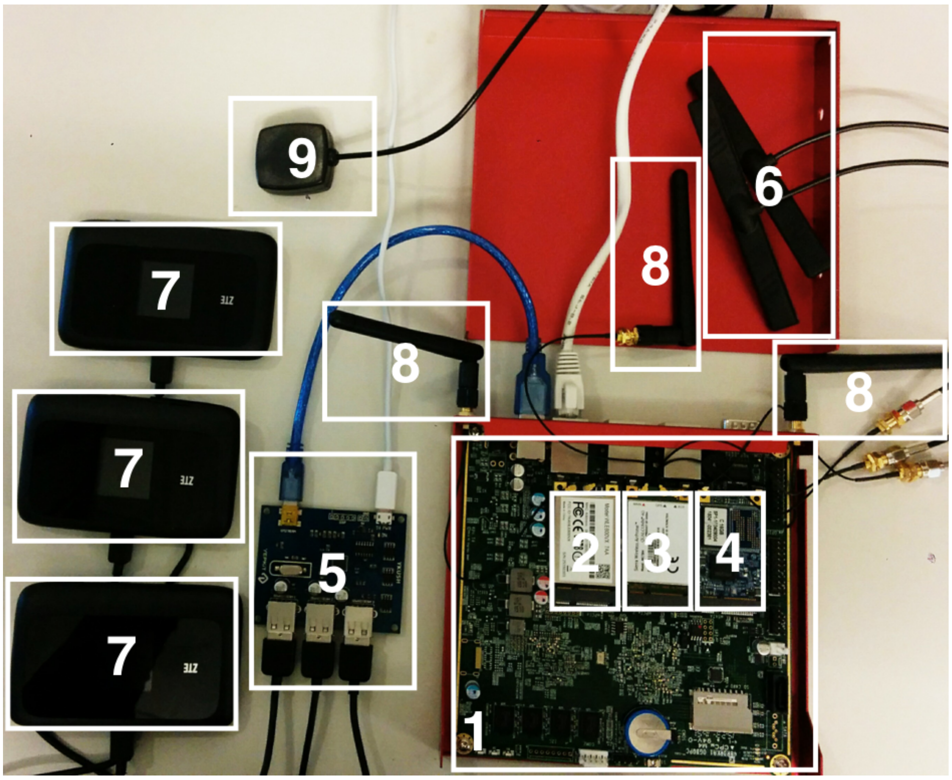


Figure 1: *The MONROE stationary node with all the main hardware components installed.*

The base board for the MONROE measurement node is the APU1D4[2] system board, which we show in Figure 1 in block no. 1 and further specify in Table 1. MONROE aims to enable mobile broadband performance testing, protocol and application experiments and modifications. In order to support such a wide variety of use cases, we design a node that runs a Linux distribution and accessorize it with the necessary hardware blocks to ensure that we are not limited by CPU, memory capabilities or storage space.

In order to capture the end-user experience, we focus on supporting typical end-user equipment like different types of USB-based devices (USB modems and MIFIs). Moreover, MONROE aims to provide WiFi connectivity mimicking multi-homing in smartphones with both MBB and WiFi interfaces, to allow experimenting on different access technologies as well as to explore new ways of combining them to increase performance and robustness. Each measurement node supports up to 3 different MBB operators (where available) and has WiFi connectivity. For supporting three MBB operators, we use three CAT4 ZTE MF910 (block no. 7 in Fig. 1) that we connect to the node through a powered USB hub (block no. 5 in Fig. 1). The

[2] http://www.pcengines.ch/apu1d4.htm

MONROE software supports also USB sticks and smartphones. We will continue testing CAT6 modems for future versions of MONROE nodes. In addition, we use a Sierra Wireless MC7304 miniPCI express card (block no. 2 in 1) in the APU for maintenance, updates and transfer of results. Finally, the MC7304 provides GPS to the node.

3 Hardware Requirements

MONROE is a Europe-wide extension of the NorNetEdge (NNE) project, which SRL has been successfully coordinating over the past 5 years at the national level in Norway. NNE is funded by the Norwegian government and the purpose of the project is to measure different performance, quality and stability aspects of the available mobile broadband (MBB) networks in Norway. NNE consists of a few hundreds stationary nodes measuring up to 5 operators each. NNE has been using a single-board node with 7 USB ports and one LAN RJ45 port custom-made in a small factory in China. The experience we have accumulated during the NNE hardware design and subsequent platform maintenance serve as background for the MONROE node selection process. However, compared to the NNE project, MONROE is adding additional features that put additional requirements to the node.

MONROE has a stronger focus on mobile nodes, which require more robust equipment and recovery procedures. The node must also support GPS in order to track routes and mobility patterns. MONROE also promises to support WiFi in at least client mode. Moreover, we need to support normal user equipment in order to capture realistic user experience. Most important, MONROE will support a varying set of experiments and access by external users, which add requirements in terms of memory and CPU capabilities. Thus, we derive a wide list of requirements that we need to consider in the selection process.

In this section, we expand on these requirements, which we classify in general node requirements (both for mobile and stationary MONROE nodes), stationary node requirements and mobile node requirements.

3.1 General Node Requirements

The following list gives an overview of the general requirements when selecting the main hardware components (base node , modems, etc.) that will be a part of both the stationary and the mobile nodes. With *base node*, we mean the hardware component that runs the operating system and to which modems can be connected.

1. **Linux-support:** Linux is the only available operating system with sufficient hardware support that offers the flexibility MONROE needs, both in terms of core software and measurement experiments. In addition, most of the network protocols that are of interest for potential MONROE users are available as Linux-implementations. Thus, we must be able to install and configure Linux on the measurement node.

2. **MBB and WiFi Connectivity:** The MONROE node must connect to 3 MBB operators (where applicable) and also support WiFi. This means that a complete node must provide at least 3 interfaces where we can connect the MBB modems. We define as a minimum requirement the support for LTE CAT4, with LTE CAT6 as a future option in the subsequent MONROE deployments. CAT4 is the current baseline for most operators and provides sufficiently high bandwidth to handle most tasks. The selected WiFi card must support client mode and preferably access point mode , as well as 2.4GHz and 5GHz.

3. **Mimic User Equipment and Experience:** MONROE has a goal of conducting measurements and experiments that reflect the performance experienced by real applications and users. A complete node

should therefore be able to support modems and equipment provided by operators, which at current time is mostly mobile hotspots, routers and smartphones.

4. **Processing Power and Data Storage:** MONROE must support advanced experiments that require a fairly powerful CPU and sufficient available memory. In addition, enough storage space (within reason) must be provided for the experiments and the experiment results.

5. **Minimize external intervention:** The complete node should be designed in such a way that host maintenance is reduced to a minimum. In this sense, we should be able to remotely power cycle the node, as well as the USB modems individually.

6. **Hardware Cost:** MONROE has a fixed budget to invest in the 250 complete nodes, and hence we must seek the components that can be affordable for the project, while not compromising on performance. We have limited our search to finding complete nodes under EUR 1,000.

7. **Availability:** In the eventuality of hardware failure, in order to ensure quick delivery of replacement hardware or to support potential rapid expansion of MONROE, all selected hardware must be available from reliable suppliers with high availability.

3.2 Stationary Node Requirement

1. **Connectivity:** For stationary nodes, it would be beneficial to also be able to connect to fixed networks over Ethernet/RJ45 for maintenance and/or measurements. Thus, the node must be equipped with at least one, but ideally two Ethernet-ports. One will be used for measurements over WAN, while the other will be used for maintenance since it provides an easy way to access deployed nodes.

3.3 Mobile Node Requirements

1. **Connectivity:** The mobile nodes must support an alternative SIM card for maintenance purposes, besides the 3 MBB connections for experiments.

2. **Support for GPS:** For mobile nodes it is a requirement to support GPS devices that can receive signals inside buses and trucks.

3. **Node Sturdiness:** A completely assembled node should function as intended aboard buses and trucks where the environment is challenging and includes vibration, temperature variance, humidity and highly variable electrical power conditions. Thus, selecting robust and reliable hardware is important. At the same time, it should be easy, for example, to disassemble the node and replace components when something breaks.

4. **Physical Size Limit:** Due to space constraints on buses and trains, the MONROE node has to meet strict size requirements. The entire MONROE node (with external devices and box) should fit inside a space of dimensions 30x30x12 cm, which is the space available in Italian busses that will host MONROE nodes.

4 Hardware Selection

The process of hardware selection implies testing, evaluating and comparing different alternatives for the MONROE node components and accessories. We present our final selection of hardware components for the MONROE node in Section 2. However, reaching this final decision implied extensive previous testing and evaluation of different options for each of the MONROE components. In this section, we discuss the other solutions we considered within the consortium, we describe how each complies with the full set of requirements and justify the decision of selecting the APU1D4 system/router board as the base for the MONROE measurement node.

4.1 Selection of base node

Celerway and SRL leveraged their industrial and research experiences from building and running the NNE research platform (SRL) and from the design of a commercial network aggregation product (Celerway). Within the NNE project, focus was mostly on single board computers (SBCs). SRL's first selection for the NNE node was based on Beaglebone with Dlink USB hub and USB modems. This solution proved to be unstable in terms of hardware failures. Thereafter, SRL decided to build a customized node from Dynsense with multiple USB ports to support USB modems. Keeping an industry-oriented mindset and a commercial angle, Celerway has been evaluating over the last years different router boards and off-the-shelf routers for use with their commercial multi-network OpenWRT-based router software solution. Celerway is currently offering products based on Linksys and TP-Link routers, PC engines APU system/router board and routers from ZBT.

Newest versions of the previously mentioned routers, boards and customized nodes have been revisited for a functional evaluation with respect to the MONROE requirements we defined in Section 3. In addition, some other node types and vendors have been evaluated. In the following, we give a brief description of the different alternatives we considered for MONROE and whether they fulfilled the list of requirements.

NNE node from Dynsense: We considered using the custom-made NNE node from Dynsense[3] also in MONROE. However, this node has become quite old and shows limitations in terms of memory and CPU capabilities. Its 7 USB ports give many options in terms of expanding the node, e.g., WiFi, GPS and USB modems can be connected as USB. However, there are some limitations in terms of AC dual channel WiFi USB options. In addition, USB devices tend to crash, and the NNE node does not support individual power cycling of USB ports, meaning that the whole node must restart in order to fix one device crash.

Another challenge with customized HW is that some drivers and software are not maintained and improved by a larger community. SRL has also experienced that the supplier does not prioritize small orders, and hence delivery time for new batches of hardware can be quite unstable and long. We have discussed if we should do an updated design to improve performance, USB power cycling, internal support for WiFi etc, but the MONROE timeline, budget constraints and unreliable availability made us conclude not to go for such a solution. Furthermore, NNE and MONROE have joined efforts to find a new common node for both projects.

Industry-grade multi-network routers: These are routers with built-in miniPCIe modems made robust and rugged for buses, trains etc. Example vendors are Nomad Digital[4], Viprinet[5], Goodmill systems[6]. We concluded early that such solutions are not viable candidates for MONROE for several reasons. The cost is several thousand euros, hardware (CPU, memory) and software (kernels) are often not latest versions because of the robustness requirement, and access to drivers and OS were limited.

[3] http://dynsense.com
[4] nomad-digital.com
[5] www.viprinet.com/en
[6] www.goodmillsystems.com

Off-the-shelf routers: Celerway has worked with and tested a majority of relevant OpenWRT[7] off-the-shelf routers (e.g. TP-Link, Linksys, Asus, Dlink) during the past 5 years. They meet very well the requirements of cost, number of network interfaces, stability, availability and flexibility or likeliness to user equipment. However, CPU, memory and storage are limiting resources when running heavy experiments. RAM is often limited to a few hundred MB and there is no internal storage. We have also experienced that throughput is CPU bound when sending data through the linux/openWRT stack. For these reasons, this is not our preferred solution. Nevertheless, the MONROE software for the measurement node is compatible to also run on such routers.

Mini PCs: We have tested Mini PCs like different versions of Intel NUC[8]. They meet very well the requirements of CPU, memory, storage and availability. However, they support a limited set of network interfaces and antennas. In addition, the cost for a complete node based on for instance a NUC is quite high and does not meet the requirement we previously imposed. For these reasons, we do not select this solution for the MONROE node. Nevertheless, the MONROE software for the measurement node is compatible to also run on Mini PCs.

Single board computers: We functionally evaluated and also tested some candidate single board computers, e.g. Raspberry Pi[9], Odroid[10], Beaglebone/Beagleboard[11]. They face the same challenge as Mini PCs in terms of support for network interfaces and antennas. In addition, some of them have limited CPU and storage capabilities. We have also tested and found Raspberry Pi and Beaglebone to be too unstable in mobile environments. For the reasons above we discard this solution for the MONROE measurement node. Nevertheless, the MONROE software for the measurement node is compatible to also run on most single board computers.

Router boards, kits: We have evaluated a set of Router boards and kits from Mikrotik[12], Gateworks[13], Global scale technologies[14], Sigarden[15] and PC Engines[16]. Such boards provide a good range of network interfaces and extensions, in addition to good availability. Mikrotik are, however, somewhat expensive and also have limited CPU, storage capacity and limited access to software drivers. Gateworks also fails to meet the cost requirements and, additionally, we found instabilities in some interfaces. Mirabox showed good performance for reasonable cost, but we experienced instabilities in terms of WiFi and heating. Sigarden hardware showed limited performance and extension options. From PC Engines, we evaluated the ALIX and APU boards. They are both used widely in industrial applications and for research with large communities. The ALIX board showed some limited performance and limited options for network interface extensions. The APU board, on the other hand, met all the requirements and was selected as the MONROE base node. Figure 2 shows the APU board that we selected for the MONROE node.

During our selection process, we also learned that the WiRover[17] project in the US employs the APU for measurements on board buses with great success. The coordinator of the WiRover project is Prof. Suman

[7] https://wiki.openwrt.org/toh/start
[8] http://www.intel.com/content/www/us/en/nuc/overview.html
[9] www.raspberrypi.org
[10] http://www.hardkernel.com
[11] http://beagleboard.org
[12] http://www.mikrotik.com
[13] www.gateworks.com
[14] www.globalscaletechnologies.com
[15] www.sigarden.com
[16] www.pcengines.ch
[17] http://research.cs.wisc.edu/wings/projects/wirover/index.html

Figure 2: *The APU system board we use as base node. We design the MONROE hardware around it by adding several accessories.*

Banerjee, who is also a part of the advisory board for MONROE.

4.2 Hardware design around APU1D4

We decided to build the MONROE measurement hardware around the APU board, which is designed by PC Engines in Switzerland. The company has existed for 20 years and was founded by current principal Pascal Dornier, who is MONROEś main contact in PC Engines. We provide a brief specification of the APU and components we use for MONROE in Section 2. For full specifications, we refer the reader to the PC Engines web pages[18].

We use the available 2 miniPCI slots for WiFi and LTE, using the cards we describe in Section 2. WiFi AC cards provide up to 3 antenna connectors, and LTE cards provide 1 main, 1 diversity and 1 GPS antenna connectors (3 in total), which means that MONROE needed an enclosure with 6 antenna holes. PC Engines makes a special enclosure for MONROE that is based on their standard red enclousure[19].

With APU1D4 as the MONROE base node, we move on to selecting node accessories that provide full functionality to the node and allow us to fulfill the requirements we defined in Section 3.

WiFi connectivity: For WiFi connectivity, given that the APU has 2 available miniPCI express slots, we limited our search to Dual band AC miniPCI express cards that can be used in both access point and client mode (mandatory). Support also for access point mode is preferred for easy local maintenance access on busses etc. We evaluated cards from Compex, Sparklan and Azurewave. We concluded that both Compex and Sparklan cards are stable with good performance. Due to cost and the fact that PC Engines provides Compex as standard, we selected Compex WLE600VX.

[18]http://www.pcengines.ch/apu1d4.htm
[19]http://www.pcengines.ch/case1d2redu.htm

Table 2: *Base node comparison. Green row shows the option we selected for MONROE.*

Base Node	Pros	Cons
NNE node from Dynsense	• Many interfaces in terms of 7 USB ports • Size is small	• CPU and Memory are limited • Not optimal WiFi and GPS support • Lack power cycling of USB ports • Uncertain availability and driver support
Industry-grade multi-network routers (Nomad Digital, Viprinet, Goodmill systems)	• Rugged and built for mobile vehicles.	• Expensive • CPU, memory and kernels are somewhat old • Access to drivers and OS are limited
Off-the-shelf routers (TP-Link, Linksys, Asus, Dlink)	• Low cost • High availability • Many network interfaces • Proved to be stable in vehicles	• Limited CPU, memory, and storage
Mini PCs (Intel NUC)	• Very good CPU, memory and storage capabilities • Good availability	• Expensive • Limited support for network intefaces
Single board computers (Raspberry Pi, Odroid, Beaglebone/Beagleboard)	• Medium cost • High availability	• Limited support for network interfaces • Unstable in rough environments
Router boards, kits (Mikrotik, Gateworks, Global scale technologies, Sigarden and PC Engines)	• Many network interfaces and extension options • High availibility • PC Engines' APU system board fulfills the most requirements	• Some are expensive • Some have unstable drivers

MBB connectivity: The most commonly used modem types have been USB sticks, MiFis (mobile hotspots), smartphones and miniPCI express cards. We collaborated with the Swedish supplier Techship in order to test and evaluate miniPCI express modems. USB sticks and MiFis are, however, the most common user equipment provided by MBB operators. ZTE and Huawei have been dominating this market in Europe for many years. We have therefore been in close contact with both vendors in order to get first hand information of future product releases, and driver support. We have also discussed within the MONROE consortium the possibility of using smartphones as modems.

In order to be able to support 3 MBB operators with USB devices (as per the list of requirements in Section 3), the APU (with only 2 USB ports) must be extended with an USB hub. Additionally, we need to also account for device power considerations and the need to ensure as little external intervention as possible. For example, USB sticks can peak over with more than 1A power consumption in bad coverage areas. Since the APU board only has 2A in total, a powered USB hub would be needed. We discuss USB hub alternatives later in this section.

Many operators in Europe are upgrading from LTE CAT4 (150Mbit/s download speed and 50Mbit/s upload speed) to LTE CAT6 (300 Mbit/s download speed and 75Mbit/s upload speed) these days. According to our list of requirements (Section 3), we have a minimum requirement of CAT4, but preferably find a solution for CAT6. In order to be able to compare operators, we have also had the requirement that we will use same modem type for all operators. We next give a brief description of the alternatives and our evaluation.

- **miniPCI express:** The APU only has one available slot for miniPCI express modem. We were not able to find any external miniPCI express hubs or similar that could be used to extend the APU. Furthermore, miniPCI express is not regarded as normal user equipment and will hence not be representative for equipment provided by operators. Thus, we had to discard this alternative for MBB connectivity. Nevertheless, we valued the opportunity in having a dedicated management interface to the node for maintenance, uploading software/experiments and results. Furthermore, miniPCI express modems come with a GPS connection, and hence we could have built-in GPS in the APU. Thus, we performed extensive tests of different miniPCI express cards to be used in the APU. We limited the evaluation to CAT4 modems with GPS. We evaluated modems from ZTE, Huawei, Sierra Wireless and Simcom, all provided by Techship in Sweden. We were not able to get the ZTE and Huawei modems to reach stable performance with the APU. Sierra Wireless and Simcom worked well. In the end, we selected Sierra Wireless MC7304 based on the fact that this is one of the most popular and stable modems currently available. It is also the modem that we have been using for the longest time.

- **USB sticks:** USB sticks have one advantage in that they have no battery, and crashed modems will restart during node power cycling. Both ZTE and Huawei claim that they will stop producing USB sticks and only focus on MiFis as user equipment in the future. Furthermore, most operators stopped using USB sticks at CAT3. Therefore, we focused the search on other alternatives. However, the MONROE software does support USB sticks, even if this is not our preferred solution for the MONROE node.

- **Smartphones:** Several smartphone vendors have released CAT6 smartphones recently, and they could hence serve as an alternative connected with USB in tethering mode. However, due to cost, high risk of theft, and the fact that a phone can do so many things other than routing that we do not control, we moved our focus to MiFis. Nevertheless, the MONROE software will also work with smartphones.

- **MiFis:** MiFis (mobile hotspots) are the most common user equipment provided by operators for MBB. ZTE and Huawei are the dominating vendors. We have been in contact with both vendors and they have been very helpful in finding solutions for MONROE. At time of selection, only Huawei had a MiFi in the market with CAT6 support (E5786). However, we were not able (in collaboration with Huawei) to utilize its full potential in Linux. In addition, we were not able to auto start it when it receives power over USB. This is a very important feature as batteries will be drained when busses are parked and turned off. If the MiFi then shuts down, it will never come up again without such auto start. The most commonly used (in Europe) MiFi from ZTE is the MF910, which is a CAT4 modem. With MF910, we are able to auto start when it gets power over USB, and we are also able to control reboot from the APU. Since MF910 has battery, it would be beneficial to be able to power cycle each individual USB port for draining the battery of MF910 in case of crash.

Powered USB hub: In order to support 3 MBB operators with USB devices like MiFis, USB sticks and smartphones, we needed a USB hub to complement the APU. Such a hub will be connected to one of the USB ports in the APU. Since the APU only support 2A and USB modems can peak consumption at 1A, a USB hub should also have its own power supply. Since modems of all types will at some point in time crash and manual intervention is not always possible (or should be minimized), we searched for USB hubs that could support individual per-port power cycling. It is also very important to drain batteries of crashed MiFis without shutting down the whole node.

Given the high number of requirements we defined, finding such a hub with a programming interface for implementing policies and optimization of power cycling was very challenging. However, we found the interesting new company Yepkit in Portugal working on an open source hardware and software USB hub (YKUSH)[20] with 3 ports with individual power cycling, and supporting 2A per downstream port. We have been working with this hub and its software since the start of MONROE, and it proves to be stable and flexible in terms of power control. This hub will be used in the first batch of MONROE nodes. It will be used with a USB A - USB Mini B 2.0 cable for data to/from the APU and a USB A - USB Micro B 2.0 cable (supporting minimum 2.1A) to the power source. Input voltage is 5V.

4.3 Node Accesssories

In Table 3 we list all the node accessories we need to assemble the mobile and stationary nodes. The APU with the main components and all other accessories should fit into a box for installation within hosts. Also, the smaller the box, the more easy the installation in busses and trucks would be. We have selected a box that fits the standard mounting size in GTT busses (Torino), which is a main host of mobile nodes. The supplier is Gewiss and the size is 30x20x12cm to comply with the requirements list.

We use the same box for all installations, so all nodes experience the same coverage conditions. We use metal strings, loctite, double sided tape and duct tape to fasten all components in the box. All components are mounted inside the box with the exception of a GPS antenna and a power cable that comes out, and an ethernet cable for local access.

Special needs for mobile nodes: Busses and trucks do not provide normal AC 110/220V AC output for the APU and the YKUSH hub. Such vehicles come with various DC voltages ranging from 12 to 110, while the APU needs 12V and the hub 5V. This brings to our attention the need to buy converters to be used in busses. We must test these converters for each type of vehicle. Converters need to have a wide range of supported input voltages as big spikes may occur, for example, when busses are started. In some busses, we will mount the boxes on special vibration blocks. Different vehicles also require extra fuses. Mobile nodes have an advantage in that they shut down power several times a day. This means that APU and hub will be power

[20] www.yepkit.com/products/ykush

Table 3: *List of the node accessories for deployment (not included in Table 1).*

Component	**Additional comments**	**Node type**
AC adapter 12V 2A euro for IT equipment[6]	With Euro plug. For the APU board. Will be ommited for Mobile nodes.	All
RF interface cables[1]	We include 6 interface cables.	All
USB A - USB Mini B 2.0 cable for data[7]	Between USB hub and APU.	All
USB A - USB Micro B 2.0 cable to power source	Must support at least 2.1A, exact cable not ordered yet. High availability.	All
USB wall plug[2]	With Euro plug. Should have minimum 2.4A output per port.	Stationary
Box 30x20x12 cm[3]		All
GSM socket from Wolf Guard[4]		Stationary
2(3) outlets extension [5]	Plug must be adjusted for each country. Placed inside box and used for USB wall plug and AC adapter for APU.	Stationary
2 x Power converters[6]	One for APU (12V-2A)and one for USB hub (5V-3A). These must be tested and ordered per installation as different busses require different input voltage and fuse requirements. This will be done in collaboration with the hosts of mobile nodes.	Mobile

Complete component specifications:
[1] https://techship.se/products/interface-cable-sma-ipex-15-cm-pigtail/
[2] https://www.anker.com/products/A2021211
[3] http://goo.gl/J4lNLg
[4] http://www.chinawolfguard.com/WIFI-GSM-Wireless-Smart-power-Switch-58.html
[5] http://www.clasohlson.com/no/3-veis-grenuttak/36-1108
[6] http://www.pcengines.ch/ac12veur2.htm
[7] http://manhattan-products.com/hi-speed-usb-device-cable11

cycled quite often, potentially fixing crashes and other errors and no intervention from our side is needed to force the power cycling.

Special needs for stationary nodes: Unlike for the mobile nodes, power cycling does not automatically happen in stationary nodes. Thus, in order to trigger power cycling and repair APU and hub crashes, we evaluated different GSM sockets. A GSM socket can be controlled via SMS in order to turn power on and off. We have evaluated different suppliers and models, and selected one that is simple and without buttons and too many special sensors that might interfere with our control. We have chosen a GSM socket from Wolf Guard. For stationary nodes, we will use a 2-socket outlet extension inside the box for the APU and hub power adapters. This connects to the GSM socket connected to a wall socket in the host location.

5 Verifying Node Applicability

The fully assembled MONROE node consists of a large set of affordable network equipment with multiple connections and cables, which we will deploy in uncontrolled real world environments (in the case of mobile nodes - buses, trams, delivery trucks, and in the case of stationary nodes - train stations, public spaces, homes). The tough conditions under which some of the nodes must operate make it imperative for us to understand and prepare for cases of failures in node functionality which, as with any operational large-scale measurements platform, are likely to occur. In line with our list of requirements, it is of utmost importance for us to be able to recover the node with minimal external intervention from the host of the node. We were able to identify early on the potential points of failure in the MONROE node (i.e., USB devices, cables, power adaptors) and thus adjust the hardware design to address those issues. By integrating MiFis with auto-start function, power cycled USB ports (via the powered USB hub) and a controlled power-cycling function for the stationary MONROE nodes (via the GSM power socket), we present in this report a hardware design proposal that allows for failure recovery with minimal external intervention from the host of the measurements node. In order to verify this claim, validate the node applicability and identify potential weaknesses, we have tested the MONROE node in different environments. Next, we describe the environments where we test our node and discuss our findings.

5.1 Processing load impact on temperature

The APU board can reach high CPU temperatures during full load. We tested the APU under full CPU load during two days in order to see how the APU temperature affects other components in the box we use to assemble all equipment. We have measured up to 90 °C in the CPU temperature sensor. However, inside the box, we do not measure more than 30 °C, which means that other components should not be affected by the APU heat.

5.2 Environment temperature and humidity stress tests

We have tested all components during a continuous period of 4 hours in a controlled environment with 80 °C and 80% humidity. In Figure 3 we show the MONROE node inside the steam oven we used to create the heat and humidity conditions for stress testing. We have thus found that the MiFis' sensors force them to shutdown when they measure more than 55 °C and 60% humidity. However, when temperature and humidity decreases below these numbers, the MiFis auto restarted. All other components passed this stress test.

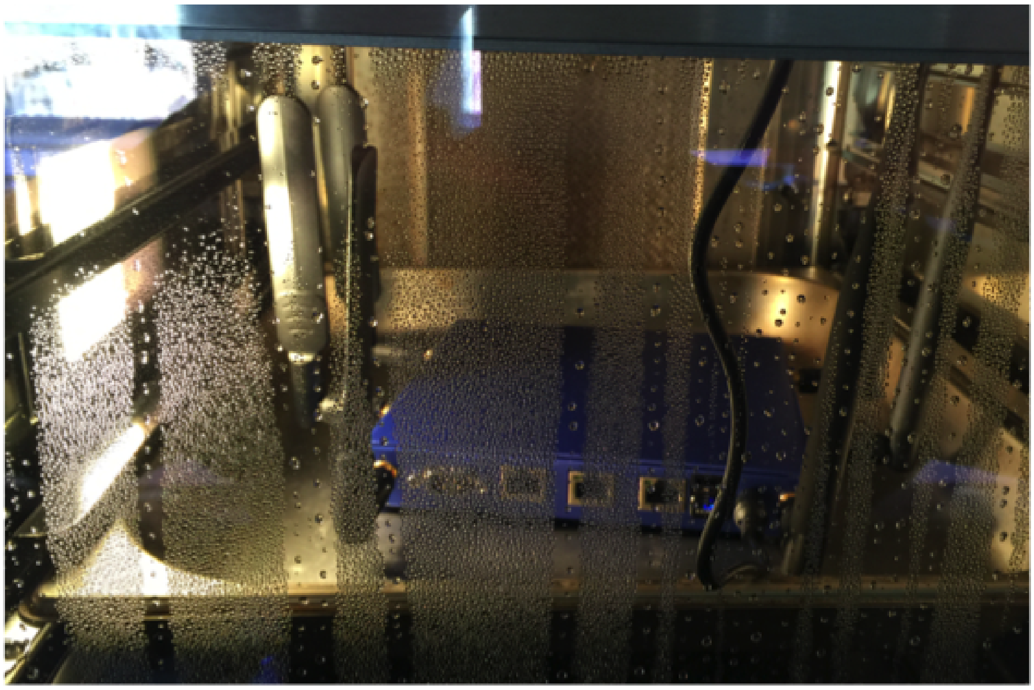


Figure 3: *The MONROE node inside steam oven for temperature and humidity stress testing.*

Additionally, we have tested all components for a continuous 3-hour period every day during 3 weeks in an environment with 70 °C and 60% humidity. All components passed the stress test.

Given that we will deploy a fraction of the MONROE nodes in environments with low temperature (i.e., mobile and stationary scenarios in Norway and Sweden), we also test the behaviour of the node at very low temperatures. We have monitored the functionality of a prototype node operating during a continuous period of 8 hours in temperature of approximately -10 °C. All components passed the stress test.

5.3 Mobility stress tests

As we previously mentioned, one main focus for MONROE is the deployment of measurements hardware in mobility scenarios, such as public transportation or personal vehicles. It is thus very important to ensure the normal functionality of the node under mobility conditions. To this end, we have tested the functionality of the node in three different scenarios, namely (i) inside a personal vehicle, (ii) on-board a regional bus operating regularly in the West Coast area (Sogndal) in Norway and (iii) on-board a local city bus operating daily in Torino, Italy.

We have temporarily deployed a complete mobile node in a personal car for period of 1 month in June and July 2015, using a 12V to 220V converter. All components functioned normally throughout this test period.

We installed a complete MONROE node on a bus on the west coast of Norway in November 2015, and on a bus in Torino in December 2015. In Figure 4 we show the fully assembled mobile MONROE node, with (a) a view inside the box enclosure with all the elements fixed to the internal walls and (b) the box mounted inside the Torino bus. Both nodes are still operational at the time of writing. In Figure 5 we show the trajectories of the two mobiles nodes which we are able to reconstruct from the GPS data we receive from the node operating aboard the two buses in (a) Torino, Italy and (b) Sogndal, Norway.

During the testing period, we have however experienced a node failure caused by converter malfunction aboard the bus operating in Torino. We also found that unstable power supplies can cause unstable USB

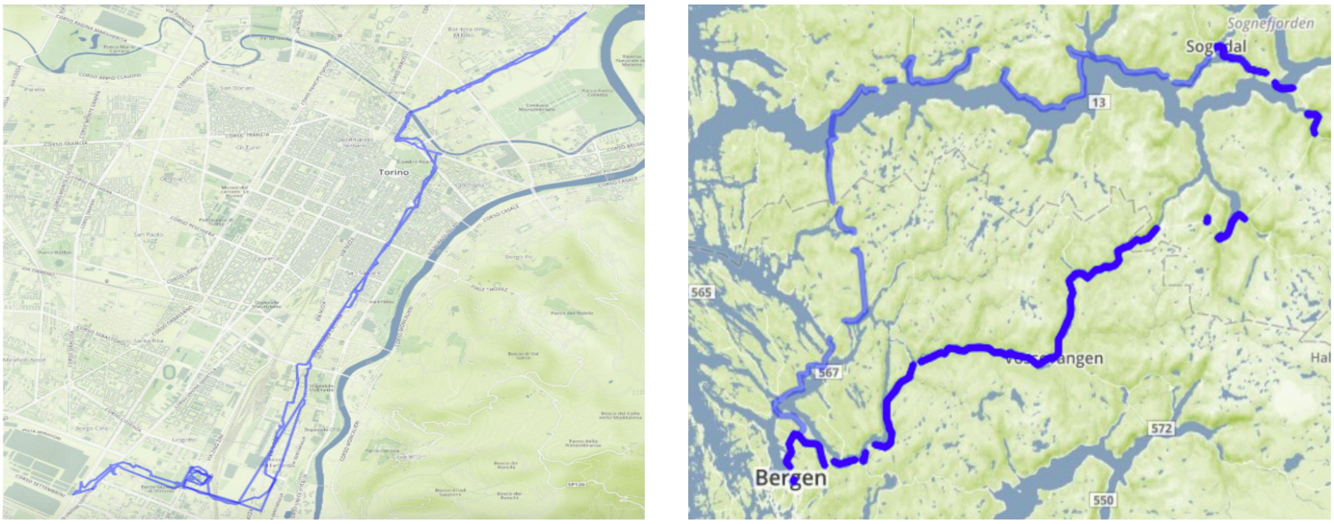
Table 4: *Data transfer limitations.*

Component	**Theoretical performance**	**Measured performance**	**Comments**
Disk, Phison 16d, APU1	4000 Mbps	2500 Mbps	Specification: http://goo.gl/IOwTo3
Memory, APU1D4	545 Gbps	112/128 Gbps i/o	
CPU, APU1, AMD G-T40E, 1 GHz dual core	Not specified by vendor	Sysbench 0.4.12: CPU benchmark time: 95s	Sysbench homepage: http://goo.gl/64jBHS
Realtek R8168 Ethernet, APU1	1000 Mbps	935 Mbps	Specification: http://goo.gl/0GuchC
WAN-LAN with Realtek R8168 Ethernet, APU1	1000 Mbps	935 Mbps	
USB 2.0 ports, APU1	480 Mbps	205 Mbps	
LAN port to USB, APU1	480 Mbps	205 Mbps	
YKUSH USB hub	480 Mbps	235 Mbps	Specifiaction: https://goo.gl/GDAnOF
WiFi Compex wle600vx	867 Mbps	NA	Specification: http://goo.gl/InTLHM
LTE Sierra Wireless MC7304	150 Mbps downstream and 50 Mbps upstream	120 Mbps downstream	(Limited by operators) Specification: http://goo.gl/g1esxO
ZTE MF910	150 Mbps downstream and 50 Mbps upstream	120 Mbps downstream	(Limited by operators) Specification: http://goo.gl/TCgznD

(a) Assembled mobile MONROE node, showing components fixed inside white box enclosure.

(b) Mobile MONROE node deployed on-board the bus in Torino.

Figure 4: *Mobile MONROE node.*



(a) Torino route.

(b) Sogndal route.

Figure 5: *Mobile MONROE node.*

power and coverage of modems. Therefore, we are still working on improving power stability on busses.

5.4 Performance limitations

After extensive testing, we provide in Table 4 an overview of data transfer capabilities of the different components, which is important input for future experiment design. As a main take-away, we find that the most important bottlenecks for experimenters to be aware of are the CAT4 modems and USB port speeds.

6 Conclusions

In this deliverable, we reported on the hardware design and selection for the MONROE measurement node. Based on our evaluation, we presented in Section 2 the current final selection for the MONROE node. We defined the selection criteria based on different aspects of MONROE, including the diversity in terms of MON-

ROE use cases, the environment where the node operates (stationary, mobile), the appeal towards external users and the cost of the equipment. We chose to design the MORNOE node around the APU14D system board, which met majority of the requirements we identified in Section 3. We listed in Section 4 all the other alternatives for the base node that we have evaluated. In december 2015, PC Engines released an updated APU router board (APU2) for pilot testing, with updated CPU, DRAM and USB. However, at the time of hardware design and selection, this option was not available for testing. This is why we have decided to deploy a fist batch of MONROE nodes built around the APU1, which we were able to stress test, as per Section 5. In the upcoming deliverable D2.2 "Node deployment: Report on deployment process" we will provide more details on the deployment strategies and success of the first deployment campaign. We are currently testing the APU2 system board and we are considering it for a future deployment of upgraded MONROE nodes. Additionally, we are considering upgrading the MONROE node with CAT6 and USB 3.0 options we are currently testing.

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