

RESEARCH CENTRE

Inria Centre
at **Université Côte d'Azur**

2023

ACTIVITY REPORT

Project-Team

DIANA

**Design, Implementation and Analysis of
Networking Architectures**

DOMAIN

**Networks, Systems and Services,
Distributed Computing**

THEME

Networks and Telecommunications

Inria

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Project-Team DIANA

Creation of the Project-Team: 2015 July 01

Keywords

Computer sciences and digital sciences

- A1.1.13. – Virtualization
- A1.2.1. – Dynamic reconfiguration
- A1.2.2. – Supervision
- A1.2.3. – Routing
- A1.2.4. – QoS, performance evaluation
- A1.2.5. – Internet of things
- A1.2.9. – Social Networks
- A1.3. – Distributed Systems
- A1.3.3. – Blockchain
- A1.3.4. – Peer to peer
- A1.3.6. – Fog, Edge
- A1.4. – Ubiquitous Systems

Other research topics and application domains

- B6.2. – Network technologies
- B6.2.1. – Wired technologies
- B6.2.2. – Radio technology
- B6.2.3. – Satellite technology
- B6.3.2. – Network protocols
- B6.3.3. – Network Management
- B6.3.4. – Social Networks
- B8.5.2. – Crowd sourcing
- B9.1.1. – E-learning, MOOC
- B9.5.1. – Computer science
- B9.5.6. – Data science
- B9.8. – Reproducibility
- B9.10. – Privacy

1 Team members, visitors, external collaborators

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- Naomi Kirimi [INRIA, Intern, from Jul 2023 until Sep 2023]
- Stefano Lioce [INRIA, Intern, from May 2023 until Oct 2023]
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- Harikrishna Kuttivelil [INRIA, until Mar 2023]
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External Collaborator

- Nathalie Currid [UNIV COTE D'AZUR, from Apr 2023]

2 Overall objectives

2.1 Presentation of the team

The overall objective of the DIANA project-team is to provide network architectural support for improving citizen rights in the Internet. To do so, we work to provide service transparency and user data control in the context of hundreds of billions of both wired and mobile devices. Our methodology includes advanced measurement techniques, design and implementation of architectural solutions, and their validation in adequate experimental facilities.

The high complexity of the Internet architecture, protocols and services, and the economic interests of the big stakeholders result in a lack of transparency concerning information of high interest to the connected “citizen” such as possible privacy leaks, root cause of service degradation or lock-in behavior. It is therefore important to enhance the network to provide service transparency to citizens.

On the other hand, the ossification of the Internet architecture around the IP protocol makes introduction of new functionalities in the network quite difficult. Users currently have no control on their contents and depend on big companies (e.g., Google drive, iCloud, dropbox, Microsoft OneDrive) to easily access and share data at the expense of their privacy. However, the recent development of software-defined network and network functions virtualization concepts open the perspective of faster deployment of network functionalities, as it abstracts the whole network as a single piece of software, instead of a large number of heterogeneous and dedicated devices to be configured one-by-one.

In the DIANA project-team, we have two main research directions:

- designing and deploying a measurement plane providing network service transparency,
- defining and deploying an open network architecture for user control.

Our research program is presented briefly in the next section.

3 Research program

3.1 Service Transparency

Transparency is to provide network users and application developers with reliable information about the current or predicted quality of their communication services, and about potential leakages of personal information, or of other information related to societal interests of the user as a “connected citizen” (e.g. possible violation of network neutrality, opinion manipulation). Service transparency goes beyond traditional network metrics, providing users and developers with meaningful insights into quality of experience, privacy, and protection against opinion manipulation, rather than just focusing on technical metrics like bandwidth or delay.

The Internet is built around a best effort routing service that does not provide any guarantee to end users in terms of quality of service (QoS). The simplicity of the Internet routing service is at the root of its huge success. Unfortunately, a simple service means unpredicted quality at the access. Even though a considerable effort is done by operators and content providers to optimize the Internet content delivery chain, mainly by over-provisioning and sophisticated engineering techniques, service degradation is still part of the Internet. The proliferation of wireless and mobile access technologies, and the versatile nature of Internet traffic, make end users quality of experience (QoE) forecast even harder. As a matter of fact, the Internet is missing a dedicated measurement plane that informs the end users on the quality they obtain and in case of substantial service degradation, on the origin of this degradation. Current state of the art activities are devoted to building a distributed measurement infrastructure to perform active, passive and hybrid measurements in the wired Internet. However, the problem is exacerbated with modern terminals such as smartphones or tablets that do not facilitate the task for end users (they

even make it harder) as they focus on simplifying the interface and limiting the control on the network, whereas the Internet behind is still the same in terms of the quality it provides. Interestingly, this same observation explains the existing difficulty to detect and prevent privacy leaks. We argue that the lack of transparency for diagnosing QoE and for detecting privacy leaks have the same root causes and can be solved using common primitives. For instance, in both cases, it is important to be able to link data packets to an application. Indeed, as the network can only access data packets, there must be a way to bind these packets to an application (to understand users QoE for this application or to associate a privacy leak to an application). This is however a complex task as the traffic might be obfuscated or encrypted. Our objectives in the research direction are the following:

- Design and develop measurement tools providing transparency, in spite of current complexity
- Deploy those measurement tools at the Internet's edge and make them useful for end users
- Propose measurements plane as an overlay or by exploiting in-network functionalities
- Adapt measurements techniques to network architectural change
- Provide measurements as native functionality in future network architecture

3.2 Open network architecture

We are surrounded by personal content of all types: photos, videos, documents, etc. The volume of such content is increasing at a fast rate, and at the same time, the spread of such content among all our connected devices (mobiles, storage devices, set-top boxes, etc) is also increasing. All this complicates the control of personal content by the user both in terms of access and sharing with other users. The access of the personal content in a seamless way independently of its location is a key challenge for the future of networks. Proprietary solutions exist, but apart from fully depending on one of them, there is no standard plane in the Internet for a seamless access to personal content. Therefore, providing network architectural support to design and develop content access and sharing mechanisms is crucial to allow users control their own data over heterogeneous underlying network or cloud services.

On the other hand, privacy is a growing concern for states, administrations, and companies. Indeed, for instance the French CNIL (entity in charge of citizens privacy in computer systems) puts privacy at the core of its activities by defining rules on any stored and collected private data. Also, companies start to use privacy preserving solutions as a competitive advantage. Therefore, understanding privacy leaks and preventing them is a problem that can already find support. However, all end-users do not *currently* put privacy as their first concern. Indeed, in face of two services with one of higher quality, they usually prefer the highest quality one whatever the privacy implication. This was, for instance, the case concerning the Web search service of Google that is more accurate but less privacy preserving than Bing or Qwant. This is also the case for cloud services such as iCloud or Dropbox that are much more convenient than open source solutions, but very bad in terms of privacy. Therefore, to reach end-users, any privacy preserving solutions must offer a service equivalent to the best existing services.

We consider that it will be highly desirable for Internet users to be able to *easily* move their content from a provider to another and therefore not to depend on a content provider or a social network monopoly. This requires that the network provides built-in architectural support for content networking.

In this research direction, we will define a new *service abstraction layer* (SAL) that could become the new waist of the network architecture with network functionalities below (IP, SDN, cloud) and applications on top. SAL will define different services that are of use to all Internet users for accessing and sharing data (seamless content localisation and retrieval, privacy leakage protection, transparent vertical and horizontal handover, etc.). The biggest challenge here is to cope in the same time with large number of content applications requirements and high underlying networks heterogeneity while still providing efficient applications performance. This requires careful definition of the services primitives and the parameters to be exchanged through the service abstraction layer.

Two concurring factors make the concept behind SAL feasible and relevant today. First, the notion of scalable network virtualization that is a required feature to deploy SAL in real networks today has been discussed recently only. Second, the need for new services abstraction is recent. Indeed, more than fifteen years ago the Internet for the end-users was mostly the Web. Only ten years ago smartphones came into

the picture of the Internet boosting the number of applications with new functionalities and risks. Since a few years, many discussions in the network communities took place around the actual complexity of the Internet and the difficulty to develop applications. Many different approaches have been discussed, such as Content Centric Networking (CCN) and Software Defined Networking (SDN) that intend to solve only part of the complexity. SAL takes a broader architectural look at the problem and considers solutions such as CCN as mere use cases. Our objectives in this research direction include the following:

- Identify common key networking services required for content access and sharing
- Detect and prevent privacy leaks for content communication
- Enhance software defined networks for large scale heterogeneous environments
- Design and develop open Content Networking architecture
- Define a service abstraction layer as the thin waist for the future content network architecture
- Test and deploy different applications using SAL primitives on heterogeneous network technologies

3.3 Methodology

We follow an experimental approach that can be described in the following techniques:

- Measurements: the aim is to get a better view of a problem in quantifiable terms. Depending on the field of interest, this may involve large scale distributed systems crawling tools; active probing techniques to infer the status and properties of a complex and non controllable system as the Internet; or even crowdsourcing-based deployments for gathering data on real-users environments or behaviours.
- Experimental evaluation: once a new idea has been designed and implemented, it is of course very desirable to assess and quantify how effective it can be, before being able to deploy it on any realistic scale. This is why a wide range of techniques can be considered for getting early, yet as significant as possible, feedback on a given paradigm or implementation. The spectrum for such techniques span from simulations to real deployments in protected and/or controlled environments.

4 Application domains

The DIANA project-team conducts research activities to provide network architectural support for improving citizen rights in the Internet. The main application domains of the teams are:

- Network and quality of experience measurement
- Detection of private information leaks
- Industrial deterministic networks
- Data center networks
- Deployment of future open radio networks
- Realistic simulations and reproducible experiments

5 Highlights of the year

In 2023, our team has played a pivotal role in the development of SLICES RI blueprint. SLICES-RI is a groundbreaking scientific instrument positioned to drive the discovery process in future digital infrastructures. As an integral part of the ESFRI roadmap since 2021, SLICES RI is a collaborative effort between the EU and member states, avoiding fragmentation and achieving critical mass.

Our team's efforts were focused on the definition of the SLICES blueprint. Our proposal includes defining the infrastructure baseline, augmented with a reference implementation to address technological challenges at an early stage. This blueprint, to be deployed by SLICES-RI partners, ensures a baseline service for experimenters during SLICES' operational phase starting in mid-2024. See [the blueprint page](#) for more details.

6 New software, platforms, open data

6.1 New software

6.1.1 ACQUAmobile

Name: Application for predicting Quality of User Experience at Internet Access

Keywords: Android, Internet access, Performance measure, Quality of Experience

Scientific Description: ACQUA is an Application for predicting Quality of Experience (QoE) at Internet Access. It is developed by the Diana team at Inria Sophia Antipolis – Méditerranée and was supported by Inria under the ADT ACQUA grant. The scientific project around ACQUA is supported by Inria Project Lab BetterNet and the French National Project ANR BottleNet. The project also got the approval of Inria COERLE and French CNIL for the part on experimentation with real users. ACQUA presents a new way for the evaluation of the performance of Internet access. Starting from network-level measurements as the ones we often do today (bandwidth, delay, loss rates, jitter, etc), ACQUA targets the estimated Quality of Experience (QoE) related to the different applications of interest to the user without the need to run them (e.g., estimated Skype quality, estimated video streaming quality).

The ACQUA Android application is supposed to be on one hand the reference application for QoE forecasting and troubleshooting for end users at their Internet access, and on the other hand, the feedback channel that allows end users to report to us (if they are willing) on their experience together with the corresponding network measurements so as to help us calibrating better and more realistic models. For this calibration, we are currently performing extensive, efficient and automatic measurements in the laboratory, we will count on end users to help us completing this dataset with further applications and more realistic network and user conditions.

ACQUA is mainly meant for end users, but it is also of interest to (mobile) network operators and to content providers to estimate the QoE of their customers and their networks without each time having to run expensive application-level traffic and to involve real users.

Functional Description: An application in ACQUA is a function, or a model, that links the network-level and device-level measurements to the expected Quality of Experience. Supervised machine learning techniques are used to establish such link between measurements both at the network level and the device level, and estimations of the Quality of Experience for different Internet applications. The required data for such learning can be obtained either by controlled experiments as we did in a prior work on Skype and YouTube Quality of Experience, or by soliciting the crowd (i.e. crowdsourcing) for combinations (i.e. tuples) of network- and application-level measurements and corresponding user-level Quality of Experience. Our current work is concentrating on calibrating further models for ACQUA and on using the dataset of ACQUA to understand the performance of mobile networks and user experience in the wild. We refer to the application [web site](#) of the project for further details.

Assessment: Audience = 3, Software Originality = 4, Software Maturity = 3, Evolution and Maintenance = 3, Software Distribution and Licensing = 5.

URL: <http://project.inria.fr/acqua/>

Authors: Thierry Spetebroot, Chadi Barakat

Contact: Chadi Barakat

6.1.2 ElectroSmart

Keywords: Crowd-sourcing, UMTS, GSM, Bluetooth, Wi-Fi, 4G, 3G, 2G, Electromagnetic waves, Android, LTE

Functional Description: The Internet and new devices such as smartphones have changed fundamentally the way people communicate, but this technological revolution comes at the price of a higher exposition of the general population to microwave electromagnetic fields (EMF). This exposition is a concern for health agencies and epidemiologists who want to understand the impact of such an exposition on health, for the general public who wants a higher transparency on its exposition and the health hazard it might represent, but also for cellular operators and regulation authorities who want to improve the cellular coverage while limiting the exposition, and for computer scientists who want to better understand the network connectivity in order to optimize communication protocols. Despite the fundamental importance to understand the exposition of the general public to EMF, it is poorly understood because of the formidable difficulty to measure, model, and analyze this exposition.

The goal of the ElectroSmart project is to develop the instrument, methods, and models to compute the exposition of the general public to microwave electromagnetic fields used by wireless protocols and infrastructures such as Wi-Fi, Bluetooth, or cellular. Using a pluri-disciplinary approach combining crowd-based measurements, in-lab experiments, and modeling using sparse and noisy data, we address challenges such as designing and implementing a measuring instrument leveraging on crowd-based measurements from mobile devices such as smartphones, modeling the exposition of the general public to EMF to compute the most accurate estimation of the exposition, and analyzing the evolution of the exposition to EMF with time. This technological breakthrough will have scientific, technical, and societal applications, notably on public health politics, by providing the scientific community and potential users with a unique measuring instrument, methods, and models to exploit the invaluable data gathered by the instrument. This project was supported by the UCN@Sophia Labex in 2016/2017/2018 (funding the engineer Mondri Ravi), by an Inria ADT (funding the engineer Abdelhakim Akodadi) 2017/2018, by Inria ATT (funding the business developer David Migliacci) in 2017/2018, and by the academy 1 of UCAJedi (funding a Ph.D. student Yanis Boussad) 2017/2021.

In August 2016, we released the first stable public release of ElectroSmart. On the 30th December 2022 the app has been downloaded more than 3 million times, we have 200 000 active users and a score of 4,5/5 on Google Play. On October 2022, the code has been opened with a BSD 3-Clause license on [github](#) and has currently 33 stars and 9 forks.

URL: <https://www-sop.inria.fr/members/Arnaud.Legout/Projects/electrosmart.html>

Contact: Arnaud Legout

Participant: Arnaud Legout

6.1.3 nepi-ng

Keywords: Wireless network, Experimentation

Functional Description: In the specific context of R2lab, we have created a tool suite for orchestrating network experiments, that for historical reasons we refer to collectively as nepi-ng, for NEPI new generation. An [umbrella website](#) is available.

At this point, nepi-ng has a much smaller scope than its NEPI ancestor used to have, in that it only supports remote control of network experiments over ssh. As a matter of fact, in practice, this

is the only access mechanism that we need to have for running experiments on both R2lab, and PlanetLab Europe.

The design of nepi-ng of course is modular, so that it will be perfectly possible to add other control mechanisms to this core if and when it becomes necessary.

- **asynciojobs:**
 - URL: <https://asynciojobs.readthedocs.io/>
 - Version: asynciojobs v0.17.0
 - Keywords: asynchronous programming, coroutines, orchestration
 - License: CC BY-SA 4.0
 - Type of human computer interaction: Python library
 - OS/Middleware: Linux
 - Required library or software: Python-3.9 / asyncio
 - Programming language: Python
- **apssh:**
 - URL: <https://apssh.readthedocs.io/>
 - Version: apssh v0.24.0
 - Keywords: orchestration, ssh, networking experimentation
 - License: CC BY-SA 4.0
 - Type of human computer interaction: Python library
 - OS/Middleware: Linux
 - Required library or software: Python-3.9 / asyncio
 - Programming language: Python

URL: <https://nepi-ng.inria.fr>

Contact: Thierry Parmentelat

6.1.4 Distrinet

Name: Distrinet

Keywords: SDN, Emulation, Large-scale Emulators, Network simulator

Scientific Description: Networks have become complex systems that combine various concepts, techniques, and technologies. As a consequence, modelling or simulating them now is extremely complicated and researchers massively resort to prototyping techniques. Mininet is the most popular tool when it comes to evaluate SDN propositions. Mininet allows to emulate SDN networks on a single computer but shows its limitations with resource intensive experiments as the emulating host may become overloaded. To tackle this issue, we propose Distrinet, a distributed implementation of Mininet over multiple hosts, based on LXD/LXC, Ansible, and VXLAN tunnels. Distrinet uses the same API than Mininet, meaning that it is compatible with Mininet programs. It is generic and can deploy experiments on Linux clusters (e.g., Grid'5000), as well as on the Amazon EC2 cloud platform.

Assessment: A5, SO3, SM2, EM2-down, SDL4

Functional Description: Distrinet is an extension of Mininet that relies on LXC to be distributed in the cloud, and particularly in Amazon. The extension has been designed to be fully compatible with Mininet. As using Distrinet potentially involves the collaboration of multiple machines we focused on guaranteeing the correctness (in a sense that results are trustworthy) of simulations when running on multiple machines. To speedup deployments, loading and unloading operations have been parallelised with asynchronous calls. The pool of machines used for simulations is automatically provisioned thanks to Ansible.

Release Contributions: First release

URL: <https://distrinet-emu.github.io>

Publication: hal-03000617v1

Contact: Walid Dabbous

Participants: Damien Saucez, Giuseppe Di Lena, Andrea Tomassilli, Frédéric Giroire, Thierry Turletti

Partner: Orange Labs

6.1.5 OMNET-TSN

Name: OMNET-TSN

Keywords: Real time, Network simulator

Functional Description: Time Sensitive Networking (TSN) aims at providing real time capabilities to Ethernet networks. To achieve this goal, the 2018 revision of the IEEE802.1Q standard (i.e., IEEE802.1Q-2018) provides the ability to define transmission selection algorithms for queues in IEEE802.1Q Ethernet switches.

We are developing an IEEE802.1Q-2018 simulation module for OMNeT++. The usual way to implement a simulation module is to abstract the components to be simulated and leverage the simulator functionalities. As a result, simulations can run very efficiently and scale well. The drawback is that the code base is only understandable by well trained developers and hardly understandable by engineers.

With our implementation we decided to make a direct transpose of the normative documents into the simulator such that anyone that reads the standards can read the code and adapt it if needed. This approach makes simulations runs last much longer than if the code were optimized for simulations but the major advantage is that engineers used to read standards and evaluate appliances provided by third parties can use it with minimal training.

The simulator code is implemented in C++ in Omnest (the commercial version of OMNeT++). As in most industrial environments it is extremely complex to install non corporate software, we implemented a front-end in javascript with the REACT framework. As a consequence, it is possible to install and run the simulation tool on a dedicated machine/VM/container and to drive simulations from any workstation solely by using a web browser.

Release Contributions:

- Multiple bug fixes in CBS
- CBS as a transmission selection algorithm instead of a transmission queue
- Complete tutorials for users
- Full code documentation for developer
- Delete message from QueuingFrame::handleMessage after it has been cloned to reduce memory footprint for large experiments
- Includes std algorithm library to compile on Linux std::set_intersection
- Add processing delay simulation
- Automated testing with docker

URL: <https://github.com/dsaucez/>

Contact: Damien Saucez

6.2 New platforms

Participants: Thierry Parmentelat, Thierry Turetletti, Damien Saucez, Walid Dabbous.

6.2.1 Reproducible research Lab - R2lab

Scientific work around network protocols and related software stacks requires experiments, hence experimental conditions, to be reproducible. This is a particularly challenging requirement in the wireless networking area, where characteristics of wireless channels are known to be variable, unpredictable and hardly controllable.

The R2lab wireless testbed was designed with reproducibility as its central characteristics; it is built around an isolated and anechoic chamber, featuring RF absorbers that prevent radio waves reflections, and a Faraday cage blocking external interferences. R2lab thus provides an ideal environment for running reproducible wireless experiments.

R2lab has been operated since December 2015, in the context of the FIT (Future Internet of Things) Equipment of Excellence project, and as such, it is now federated with the other testbeds that are part of the FIT initiative. As of early 2019, it has been also federated within the Fed4Fire initiative.

Available toolsets, both hardware and software, are mostly stable apart from low noise marginal deployment of new kinds of radio devices, that now encompass 5G and LoRa (from Long Range, a physical proprietary radio communication technique), among others. Our focus at this point of the project is to leverage our initial technical and financial investment, and to produce scientific work around reproducibility, particularly from a methodological standpoint, as illustrated by various [publications](#) listed in the R2lab web site.

Worth being mentioned as well, as part of a partnership with the Open Air Interface (OAI) initiative, R2lab is used on a daily basis for system-wide regression tests of the OAI stack, which in return allows us to offer up-to-date images for running OAI-based experiments. Emphasis has been put lately on offering tools that leverage kubernetes as the swiss-knife for orchestrating the deployment of a complete 5G infrastructure as an elastic set of microservices.

In 2021, the management tools on R2lab were extended to support running docker images, in addition to the historic, metal-based image format (.ndz). This allows experimenters to build their images using mainstream tools and base images. Thanks to that, we can now expose the latest OAI code as R2lab-ready docker images, both for (the Evolved Packet Core network) and RAN (the Radio Access Network).

Access to R2lab is open 24/7. R2lab is used by more than 150 users, half of them from France and the other half from all over the world (Australia, Belgium, Brazil, Canada, Chile, Spain Finland, Germany, India, Indonesia, Italy, Japan, Luxembourg, Netherlands Norway, Tunisia, Turkey, UK, US, Vietnam, etc.) to evaluate a wide range of wireless networking scenarios in realistic and reproducible environment. For more details see [R2lab home page](#). This year, two powerful Universal Software Radio Peripheral (USRP) devices were added and are currently available: [USRP N300](#) and [USRP N320](#). Each one is connected through 2x10Gbps SFP+ fibers to our SophiaNode cluster.

Two AW2S 5G Remote Radio Heads (RRH) / Remote Radio Units (RRUs) are also available: a JAGUAR 2T2R RU (CPRI Split 8), IBUmax 50MHz, MIMO 2x2, and a PANTHER 4T4R RU (CPRI Split 8), IBUmax 100MHz, MIMO 4x4. As for USRP N300/N320 devices, each AW2S RU is connected through either 2x10Gbps or 2x25Gbps fibers to our SophiaNode cluster.

The testbed includes also three other 5G modules composed of a Raspberry Pi4 device with a specific hat used to connect a 5G Quectel RM 500Q-GL module using specific kits (composed of M.2/USB3 interface and 4 antennas).

Two new 5G phones replace our old 4G phones: a HUAWEI P40 Pro and a Google Pixel 7. As the previous ones, they are remotely reachable to set up various scenarios.

The future plan is to include R2lab as an addition to the SophiaNode that is developed in collaboration with the OpenAirInterface consortium at Eurecom in the context of the SLICES-RI project.

6.2.2 SophiaNode: an open programmable 5G platform

Our project-team collaborates with Eurecom to deploy and operate an open programmable platform to test post-5G services. Last year, R2lab was connected to a sister site at Eurecom with 600 Gbps fibers forming together the so-called SophiaNode of the ESFRI SLICES-RI project. Last year we enriched R2lab with 5G professional radio units and compute resources managed by Kubernetes clusters to provide an experimental cloud-native environment to test with open source (OAI, SrsLTE) software and some commercially licensed software (e.g. Amarisoft) for 5G/6G networks supporting for example scenarios with disaggregated 5G networks elements. This year we have strongly contributed to making the SophiaNode the reference node for SLICES-RI project. As a result, the SophiaNode is the first node to fully implement the SLICES 5G blueprint. It is used as implementation reference of the other partners. The SLICES blueprint is aimed at sharing the same vision and solutions among the partners as well as proposing a plan for the design and deployment of SLICES RI. In this blueprint we proposed to define the infrastructure baseline augmented with a reference implementation, which aims at keeping a focus on the goals of the project, yet identifying technological challenges and breakthrough at the early stage of the process. Based on developments realized on the SophiaNode, the blueprint shall be deployed by the SLICES-RI partners and will provide the baseline service that will be exposed to the experimenters when SLICES will move into the operation phase (continuous integration and deployment strategy that will start mid 2024).

7 New results

7.1 Service Transparency

7.1.1 Leveraging Web browsing performance data for Network monitoring: A data-driven approach

Participants: Chadi Barakat, Naomi Krimi.

Web browsing is one of the most widespread uses of the Internet globally. Despite advancements in network performance, end users still face slow web browsing situations, which can have a range of causes such as a congested Wi-Fi network, a bad wireless signal, or a loaded network and end hosts. It is thus crucial to monitor the network and troubleshoot the specific causes of slow web browsing, as this benefits end users, operators, and internet service providers alike. Various tools attempting to actively collect web measurements through the injection of probes into the network exist. However, no solution is able to identify the specific cause of web browsing performance degradation. This contribution addresses the problem by proposing a new lightweight passive measurement solution capable of transforming web performance measurements collected from within the browser into indicators of network performance and the origin of web browsing anomalies. We validate our solution by emulating a controlled network environment, manually injecting anomalies, leveraging the measurement data available within a browser and building a predictive model that uses a random forest classifier to correctly classify the causes of web browsing performance degradation. Our solution can be used in the wild in the form of a browser plugin to monitor the network and shed light on its anomalies without actively probing it by solely relying on regular user traffic activity. This contribution has been the result of the MIT-Inria internship of Naomi Krimi, and part of the WEMON project that got funded by the Academy of Excellence "Networks, Information, and Digital Society" of Université Côte d'Azur. Within this project a postdoc will join the Diana team in 2024 to work on validating the approach in more realistic scenarios such as cellular networks, and consolidating the machine learning part of the work with further data collection and analysis.

7.1.2 Ray tracing for accurate estimation of signal power and QoS map generation in mobile networks

Participants: Bernard Tamba Sandouno, Chadi Barakat, Walid Dabbous, Thierry Turletti.

Ray Tracing is a propagation modeling approach that accurately estimates the signal power received by end users while considering the details of the environment in their vicinity. The accuracy of this estimation is at the cost of high computational load and high memory consumption due to the heavy computation performed by processes such as the Ray Generation. In this work done in collaboration with the YDATA SME in the context of the PhD thesis of Bernard Tamba Sandouno, we introduce a site-specific ray generation technique able to generate up to 1 million rays within a few seconds and a root mean square error for bandwidth estimation within 2 Mbps. Depending on the location of the antenna, the coverage area, the type of the terrain and the computational resources available, our technique gives the minimum possible number of rays required to accurately estimate end-users' signal power received and their download bitrate. The results of this work were published in [12].

We next build upon this work and use Ray Tracing as a propagation modeling approach for accurate generation of Quality of Service (QoS) maps in mobile cellular networks (signal power, bitrate, etc). The challenge here is that due to the complexity of Ray Tracing, current implementations fail to generate such maps in wide areas. In this second contribution that appeared in [16], always in collaboration with YDATA, we propose an optimization to Ray Tracing able to accurately generate QoS maps in a reasonable time. By leveraging the site-specific ray launching technique outlined above and introducing an innovative alternative to the reception test process tailored specifically for horizontal reception planes, we have achieved a remarkable enhancement in the performance of Ray Tracing. This optimization results in a nearly 1200-fold reduction in execution time, all while maintaining a minimal memory footprint of less than 2%.

7.1.3 YouTube goes 5G: QoE Benchmarking and ML-based Stall Prediction

Participants: Chadi Barakat.

Given the dominance of adaptive video streaming services on the Internet traffic, understanding how YouTube Quality of Experience (QoE) relates to real 4G and 5G Channel Level Metrics (CLM) is of interest to not only the research community but also to Mobile Network Operators (MNOs) and content creators. In this context, and in collaboration with colleagues from University of Campinas in Brazil, we collect YouTube and CLM logs with 1-second granularity spanning a six-month period. We group the traces by their context, i.e., Mobility, Pedestrian, Bus/Railway terminals, and Static Outdoor, and derive key performance footprints of real 4G and 5G video streaming in the wild. We also develop Machine Learning (ML) classifiers to predict objective QoE video stalls by using past patterns from CLM traces. We release all datasets and software artifacts for reproducibility purposes. The study will be published in WCNC [15].

7.1.4 Methodological and ethical recommendations for the evaluation of non-pharmacological interventions: results from a French study using a participatory consensus approach

Participants: Arnaud Legout.

Arnaud Legout explored, in the context of his ElectroSmart project, an experimental therapy based on Open Label Placebo to reduce symptoms of electrosensitive persons. Whereas this project has been abandoned, it introduces Arnaud to the community of Non Pharmacological Intervention (NPI) and to the NPI Society. He joined the expert committee of the NPIS and had a central role in the definition of the statistical methods to evaluate NPIS.

The term non-pharmacological interventions (NPIS) refers to health prevention and care protocols predominantly with a physical, nutritional or psychosocial focus supervised by a professional. Unlike

drugs and medical devices, no consensual model for evaluating these complex interventions existed prior to the present study because of large heterogeneity in intervention content and study protocols. This heterogeneity limited the transferability of good practices and led to a great deal of mistrust among professionals and users alike. The present study involved the co-construction of a consensual evaluation framework which meets the specificity of NPIs, participatory approach, and international standards for research in the field of health.

The study involved all French stakeholders, academic and non-academic, researchers, healthcare users, health practitioners, health operators, scientific societies and health authorities. The framework was co-constructed under the direction of a multidisciplinary committee of 22 experts through iterative, open and tracked exchanges, in four successive stages: work performed by a select committee, work performed by a larger committee, open vote by college, and finally, consultation with health authorities and scientific societies.

The framework for evaluating NPIs, called the 'NPI Model', includes 14 ethical invariants and 63 methodological invariants shared among five types of study: mechanistic, observational, prototypical, intervention, and implementation. It received the support of 27 learned societies and three French health authorities.

The creation of a standardized framework for evaluating NPIs in the French context has several advantages, as follows: i) it harmonizes and clarifies epistemological, methodological and ethical expectations of a study evaluating NPIs for researchers; ii) it ensures the results of a study are more transferable; iii) it guarantees that programs for professionals in the healthcare, prevention and social assistance sectors are more operational; iv) it facilitates efficient and safer practices for users; v) it provides better understanding for decision-makers and regulation responsible; vi) it ensures more traceable interventions for health operators; vii) it provides solutions that can be better integrated into financing strategies of insurance and social solidarity systems.

Arnaud Legout co-authored this work that is **under submission** and the official NPI model.

7.2 Open Network Architecture

7.2.1 Provable real time network updates

Participants: Damien Saucez.

Next generations of smart factories and industrial systems will rely on commodity Ethernet hardware and 5G. In this context, it is essential to provide means to guarantee that any configuration action in the network preserves network performances within known and acceptable boundaries. By means of binary decision diagrams we are building models of incremental network updates that guarantee not only latency and bandwidth constraints but also jitter and that are immune to vulnerabilities. This ongoing work is done in collaboration with Inria Nancy and Aalborg University.

7.2.2 Exploration and explanation of the Bitcoin address graph structure

Participants: Arnaud Legout.

Bitcoin is the first cryptocurrency blockchain in terms of valuation (+700B USD), it is also the most studied one. However, the internal structure of the graph of addresses is still poorly understood. The goal of this project is to explore several key aspects and this graph.

1. Bitcoin as the first cryptocurrency is used for money laundering and is victim of market manipulation. However, unlike the classical financial markets, all transactions are public. Therefore, we want to identify structural invariants in the graph that represent attempts to either launder money or manipulate the market.

2. The Bitcoin address graph is a large graph with 1 billion addresses and 10 billion edges. However, as there is no preferential attachment, its structure cannot be explained with the same core principles as social networks. We want to explore the structure of this graph and gain new insights into how financial markets start and grow.

This is an on-going work.

7.3 Experimental Evaluation

7.3.1 SLICES, a scientific instrument for the networking community

Participants: Walid Dabbous, Thierry Parmentelat, Thierry Turetletti, Damien Saucez.

A science is defined by a set of encyclopedic knowledge related to facts or phenomena following rules or evidenced by experimentally-driven observations. Computer Science, and in particular computer networks, is a relatively new scientific domain maturing over years and adopting the best practices inherited from more fundamental disciplines. The design of past, present and future networking components and architectures have been assisted, among other methods, by experimentally-driven research and in particular by the deployment of test platforms, usually named as testbeds. However, often experimentally-driven networking research used scattered methodologies, based on ad-hoc, small-sized testbeds, producing hardly repeatable results. We believe that computer networks need to adopt a more structured methodology, supported by appropriate instruments, to produce credible experimental results supporting radical and incremental innovations. In this contribution, we report lessons learned from the design and operation of test platforms for the scientific community dealing with digital infrastructures. We introduce the SLICES initiative as the outcome of several years of evolution of the concept of a networking test platform transformed into a scientific instrument. We address the challenges, requirements and opportunities that our community is facing to manage the full research-life cycle necessary to support a scientific methodology. We participated this year to the [SLICES Blueprint workshop](#) in Sorbonne University.

7.3.2 Introducing Fidelity into Network Emulation

Participants: Houssam Elbouanani, Chadi Barakat, Walid Dabbous, Thierry Turetletti.

The design and development of new network protocols, architectures, and technologies requires an evaluation phase where the researcher must provide empirical evidence for the performance of their contributions, potentially in comparison to existing solutions. In this context, network emulation has proven to be an attractive approach as it offers more flexibility compared to traditional testing platforms, and more realism compared to simulation. Network emulators provide contained, customizable, and scalable testing environments both for researchers to evaluate their contributions and for the community to reproduce their results. The major drawback of this approach in network experimentation is the use of virtual components (hosts, network switches, etc.) that do not behave with perfect similarity to the physical components they emulate, mainly due to the concurrency in using the underlay network and computing resources. We thus present in this work, that is part of the PhD thesis of Houssam ElBouanani who graduated in March 2023, a methodology to monitor emulation fidelity by measuring the network delays of emulated packets, which relies on statistical metrics to evaluate their inaccuracy. We further dig into the possible sources of emulation inaccuracy and show how our system can detect them to avoid biased experiment results. We particularly show through a common experiment scenario how undetected network emulation errors can lead to biased results. These results were published in [13]. In a follow-up work that was published in [14] (and an extended version was published in a journal [11]) and always part of the PhD thesis of Houssam ElBouanani [17], we address the problem of troubleshooting distributed network emulation, and propose a heuristic based on linear optimization to extract information about

the physical infrastructure from emulation-level packet delay measurements, in order to pinpoint the root causes of emulation inaccuracy with minimal hypotheses. We evaluate the precision of our heuristic using numerical simulations, then show how its implementation performs in a real network scenario.

7.3.3 Adding R2lab worker nodes on the kubernetes SophiaNode cluster

Participants: Damien Saucez, Thierry Turletti.

This demo aims to demonstrate how to use R2lab nodes as workers in our SophiaNode kubernetes cluster. It uses the SLICES blueprint, which automates the kubernetes (k8s) worker node setup using [Ansible playbooks](#). Basically, the demo uses one of the R2lab nodes to launch the ansible playbook that will configure the selected R2lab node(s) for the scenario and attach them to the SophiaNode k8s cluster. All the steps to reproduce the demo, documentation and code are available in [GitHub](#).

7.3.4 Deploying 5G demo on the SophiaNode/R2lab platform

Participants: Thierry Parmentelat, Thierry Turletti.

We have written a nepi-ng script that allows to run 5G OpenAirInterface (OAI) Core Network (CN) and RAN on our new SophiaNode platform. This script aims to demonstrate how to automate an OAI5G deployment on our SophiaNode Kubernetes-based cluster using worker nodes running both on PowerEdge servers on our k8s cluster and FIT R2lab nodes. The script assumes the presence of at minima one FIT node used as k8s worker node attached to the SophiaNode cluster¹ that will be used to deploy the OAI-5G scenario on the k8s cluster and within the R2lab anechoic testbed. Different gNB nodes can be used such as USRP B210 connected to k8s worker R2lab nodes, AW2S RRU (such as Jaguar MIMO 2x2 or Panther MIMO 4x4) or USRP N300 or N320 connected with fibers to the oai-gnb pod running on a k8s worker server on the cluster. Regarding UEs, different types are also possible such as 5G Quectel RM 500Q-GL devices attached to either FIT nodes or Raspberry Pi4 nodes in R2lab or 5G phones. In a nutshell, the nepi-ng script first configures the OAI-5G charts to match the parameters of the scenario, e.g., the type of USRP device used to run the gNB and the type of core-network (CN) deployment (basic or advance with different slices). Then it will set up the different nodes used to run the OAI5G functions, including the different UEs selected for the scenario. When all nodes are ready with the required configuration, orchestration of the different OAI5G functions can start through one of the k8s worker R2lab node. All the steps to reproduce the demo, documentation and code are available in [GitHub](#).

7.3.5 Deploying a Multi-access Edge Computing Platform on the R2lab platform

Participants: Thierry Turletti.

We have written a nepi-ng script to deploy the [OpenAirInterface Multi-access Edge Computing Platform blueprint](#) within the R2lab platform. The OpenAirInterface Multi-access Edge Computing Platform blueprint developed by Eurecom was only able to run on simulation mode (using rfsim). We have extended it to make it able to use USRP B210-based gNB and UE nodes (such as Quectel nodes and 5G phones) located in the R2lab platform. In the original blueprint, all the CN, RAN and MEP (Multi-access Edge Computing Platforms) docker containers were running on the same host. This modified blueprint will deploy the core-network, RAN and mep docker compose files on three different FIT nodes. All the steps to reproduce the demo, documentation and code are available in [GitHub](#).

¹see demo [7.3.3](#).

8 Bilateral contracts and grants with industry

Participants: Chadi Barakat, Walid Dabbous, Bernard Tamba Sandouno, Thierry Turletti.

8.1 Bilateral contracts with industry

Collaboration with YDATA We have started a collaboration with the YDATA enterprise on the topic of geolocation assessment of mobile network performance. YDATA is among others the owner of the [Zone Adsl website](#) to compare the Internet commercial offers in France. The activity started with a CIFRE thesis. The PhD student Bernard Tamba Sandouno started his PhD on this topic on May 2021. Currently, he is working on developing a set of algorithms to predict the geolocation performance of mobile broadband networks using a ray tracing approach coupled with wireless channel propagation models. The main challenge is in accelerating the rendering of the Radio Frequency performance maps without compromising accuracy and precision as compared to traditional approaches, so that the mapping can scale to the size of a region or a country.

Participants: Chadi Barakat, Walid Dabbous, Damien Saucez, Thery Turletti.

9 Partnerships and cooperations

9.1 International research visitors

9.1.1 Visits of international scientists

Inria International Chair In the context of Prof Obraczka's International Chair, Harikrishna Kuttivelil, PhD student supervised by her at UC Santa Cruz joined our project-team in October 2022 for a six-month visit ended in March 2023. He has been conducting research across two inter-related projects: community-structured decentralized learning, and a network simulation bridge to connect applications to network simulators. In the former, Hari has been developing a network-cognizant and community-structured approach to fully decentralized learning at the Internet's edge, exploiting the network and application affinities within the learning agents. To this end, he has been designing and implementing model-agnostic strategies for community formation. The next step is to integrate knowledge about the underlying network into the community formation strategies. He has been also developing a network simulation bridge to integrate developer applications to network simulators. This will allow him to test, evaluate and validate his network-cognizant, community-structured decentralized learning mechanisms.

Other international visits to the team Professor Sumit Roy visited the DIANA team from October 2nd to October 13, engaging in discussions with team members to explore potential collaborations in areas such as future open cellular networks, reconfigurable intelligent surfaces, and the convergence of vision and communication technologies.

Throughout his visit, Professor Sumit Roy conducted three insightful seminars. The first seminar, titled "Towards Automotive Radar Networks for Enhanced Detection/Cognition," was held at [Eurecom](#) on October 4. The second seminar, focusing on "Multi-Network WiFi Analysis & Optimization via ns-3: An Update," was an internal session for the DIANA team on October 9. The third seminar was part of the [Forum Numerica seminar series](#) at Université Côte d'Azur, where he shared his expertise on "Beyond 5G Networks: Strategic Roadmap and R&D Prospects" on October 12.

Subsequent to his visit, Professor Sumit Roy has taken on a prominent role as the Director for Wireless Networks Research at the National Science Foundation (NSF) for the next two years.

9.1.2 Visits to international teams

Manel Khelifi and Damien Saucez conducted visits to Professor Georg Carle's team at the Technical University of Munich (TUM), who are partners in the [SLICES-SC project](#), on October 24 and November 29, respectively. These visits were specifically focused on the PoS ([plain orchestrating service](#)) reproducibility framework, with the objective of seamlessly integrating it into the overall SLICES blueprint. The collaborative efforts during these visits aimed to enhance the synergy between the PoS reproducibility framework and the broader objectives of the SLICES-SC project, contributing to the project's overall success and effectiveness.

Damien Saucez has been invited to the [Academic Salon on High-Performance and Low Latency Networks and Systems](#) in Munich on November 30, to present how research infrastructures can be used to enhance reproducibility. In addition a methodology on how to realize provable experiment in real time networks has been presented and discussed with the attendance. A particular focus has been made on how to have exclusive use of real-time hardware resources in shared environments.

9.2 European initiatives

9.2.1 Horizon Europe

CONVERGE [CONVERGE project on cordis.europa.eu](#)

Title: Telecommunications and Computer Vision Convergence Tools for Research Infrastructures

Duration: From February 1, 2023 to January 31, 2026

Partners:

- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- Rice University, United States
- OULUN YLIOPISTO (UOULU), Finland
- INESC TEC - INSTITUTO DE ENGENHARIA DE SISTEMAS E COMPUTADORES, TECNOLOGIA E CIENCIA (INESC TEC), Portugal
- FINCLOUD OY (FINCLOUD LTD), Finland
- INTERDIGITAL EUROPE LTD (INTERDIGITAL EUROPE LTD), United Kingdom
- FINWE OY, Finland
- THE QUEEN'S UNIVERSITY OF BELFAST (THE QUEEN'S UNIVERSITY OF BELFAST), United Kingdom
- ALLBESMART LDA, Portugal
- GREENERWAVE, France
- EURECOM GIE (EURECOM), France
- ADTECHNOLOGIES, UNIPESSOAL LDA, Portugal
- RUTGERS, THE STATE UNIVERSITY OF NEW JERSEY (RUTGERS), United States
- BARCELONA SUPERCOMPUTING CENTER CENTRO NACIONAL DE SUPERCOMPUTACION (BSC CNS), Spain
- CSC-TIETEEN TIETOTEKNIKAN KESKUS OY (CSC-IT CENTER FOR SCIENCE LTD), Finland
- SORBONNE UNIVERSITE, France

Inria contact: Walid Dabbous

Coordinator: INESC TEC.

Summary: Telecommunications and computer vision have evolved as separate scientific areas. This is envisioned to change with the advent of wireless communications with radios characterised by line-of-sight ranges which could benefit from visual data to predict the wireless channel dynamics. Computer vision applications will also become more robust if helped by radio-based imaging. This new joint research field relies on wireless communications, computer vision, sensing and machine learning, and it has a high innovation potential because of the large domain of innovative applications it enables and the relevant know-how available in Europe. However, the full potential of this new area can only be evaluated if adequate Research Infrastructures (RI) and tools are available.

The main objective of the CONVERGE project is the development of an innovative toolset aligned with the motto “view-to-communicate and communicate-to-view”. This toolset is a world-first and consists of vision-aided large intelligent surfaces, vision-aided fixed and mobile base stations, a vision-radio simulator and 3D environment modeler, and machine learning algorithms for multimodal data including radio signals, video streams, RF sensing, and traffic traces. This toolset will be deployed into 7 RIs mostly aligned with the ESFRI SLICES-RI and improve their competitiveness.

CONVERGE will also provide the scientific community with open datasets of experimental and simulated data obtained with the toolset in the RIs, meet scientific and industrial requirements by addressing relevant 6G verticals, enhance the competitiveness of the involved companies, extend the European influence to world-wide recognised RIs, enable the creation of new RIs, contribute to the development of new environment-friendly tools, and help European Union to address its societal challenges.

9.2.2 H2020 projects

SLICES - SC [SLICES - SC project on cordis.europa.eu](https://cordis.europa.eu/project/SLICES-SC)

Title: Scientific Large-scale Infrastructure for Computing/Communication Experimental Studies – Starting Community

Duration: From March 1, 2021 to August 31, 2024

Partners:

- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- OULUN YLIOPISTO (UOULU), Finland
- TECHNISCHE UNIVERSITÄT MÜNCHEN (TUM), Germany
- INTERUNIVERSITAIR MICRO-ELECTRONICA CENTRUM (IMEC), Belgium
- FUNDACION IMDEA NETWORKS (IMDEA NETWORKS), Spain
- COSMOTEL KINIKES TELEKOMUNIKATIONEN MONOPROSOPIAE (MOBILE TELECOMMUNICATIONS SINGLE MEMBER SA), Greece
- INSTYTUT CHEMII BIOORGANICZNEJ POLSKIEJ AKADEMII NAUK, Poland
- MANDAT INTERNATIONAL ALIAS FONDATION POUR LA COOPERATION INTERNATIONALE (MI), Switzerland
- CONSIGLIO NAZIONALE DELLE RICERCHE (CNR), Italy
- SZAMITASTECHNIKAI ES AUTOMATIZALASI KUTATOINTEZET (SZTAKI), Hungary
- EURECOM GIE (EURECOM), France
- PANEPISTIMIO THESSALIAS (UNIVERSITY OF THESSALY - UTH), Greece
- IOT LAB ASSOCIATION, Switzerland
- CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (CNRS), France
- UNIVERSIDAD CARLOS III DE MADRID (UC3M), Spain

- SORBONNE UNIVERSITE, France

Inria contact: Walid Dabbous

Coordinator: Sorbonne University.

Summary: Today we are experiencing the digital transformation happening with an unprecedented pace, with the community constantly researching on new solutions to support this transformation with ample computational power and connectivity. Towards addressing such research efforts, Research Infrastructure (RI) specific to addressing Digital Sciences research efforts have been deployed worldwide, towards trying to address key aspects contrary to off-the-shelf commercial infrastructure: 1) Full control over the parameters of an experiment, 2) Repeatable experiments regardless of the physical infrastructure, 3) Valid experimental results, which are easy to cross-reference and replicate. As such, several RIs have emerged, offering experimentation services with bleeding edge resources, that otherwise are only offered only in industrial R&D laboratories, with limited functionality. Towards combating these issues, SLICES Research Infrastructure is about to be deployed, aiming to provide high quality experimentation services with emerging technologies around the area of digital sciences (5G/6G, NFV, IoT and Cloud Computing), in an Internet-scale setup. With SLICES-SC, we aspire to foster the community of researchers around this ecosystem, create and strengthen necessary links with relevant industrial stakeholders for the exploitation of the infrastructure, advance existing methods for research reproducibility and experiment repeatability, and design and deploy the necessary solutions for providing SLICES-RI with an easy to access scheme for users from different disciplines. A set of detailed research activities has been designed to materialize these efforts in tools for providing transnational (remote and physical) access to the facility, as well as virtual access to the data produced over the facilities. The respective networking activities of the project aspire in fostering the community around these infrastructures, as well as open up to new disciplines and industrial stakeholders.

9.3 National initiatives

Our team is involved in three projects within the context of the acceleration PEPR on 5G and future networks.

The 5G network and the networks of the future represent a key issue for French and European industry, society and digital sovereignty. This is why the French government has decided to launch a dedicated national strategy. One of this strategy's priority ambitions is to produce significant public research efforts so the national scientific community contributes fully to making progress that clearly responds to the challenges of 5G and the networks of the future. In this context, the CNRS, the CEA and the Institut Mines-Télécom (IMT) are co-leading the 5G acceleration PEPR to support upstream research into the development of advanced technologies for 5G and the networks of the future. The DIANA project-team is involved into 3 research projects over the ten targeted supported by the program PC1-MUST, PC2-NAI and PC10-FPNG.

9.3.1 PC1, NF MUST : End-to-end multi domain services management architecture of the networks of the future

- Coordinator : Djamal Zeghlache (IMT)
- Inria teams participating to the project : COATI, DIANA, ERMINE
- Summary : The 5G and 6G end-to-end Multi-Domain Services Management Architecture (NF-MUST) aims at automating production of inter-domain (business and application level) services for 5G, 5G Beyond and 6G networks. A challenging and still unrealized evolution today compared with single domain services or pre-established static multi-domain services that are gradually emerging in 5G and Beyond. Project NF-MUST of the PEPR 5G and Future Networks, focuses mainly on transforming client requests into end-to-end service orderings and on mapping them to resources and network level services (to be) provisioned by the multiple underlying networks. There is a clear evolution of 5 and 6G networks towards the provisioning of services involving multiple players

and multiple technologies. Project NF-MUST addresses the related roles and interactions between customers and multiple domains in connection to the other “PEPR 5G and Future Networks” projects, to ensure automated production and operation of multi-domain services across multiple providers. Besides ordering services, NF-MUST will drive the management of the life cycle of the infrastructures” provisioned services and partake in their dynamic and automated adaptation and operation. NF-MUST operates at the business subsystem (BSS) level and at the service side of the operation subsystem (OSS) level. NF-MUST interacts directly with network services treated by project 2 of the overall program.

- Role of the DIANA team: Co-supervise a PhD thesis with COATI on Efficient resource utilisation for service management in next generation networks, to start during 2024.

9.3.2 PC2, NF NAI : Network and infrastructure architectures and network-cloud-sensing convergence

- Coordinator : Gérard Memmi (IMT)
- Inria teams participating to the project : AGORA, DIANA, RESIST, TRiBE.
- Summary: The capacity to design, develop, plan, and operate networks and convergent network-cloud-sensing systems efficiently, securely and economically in terms of resource consumption. Additionally, these networks and systems will have to be working in collaboration with the various sectors of activity. These networks and systems will also need to be capable of supporting the wide variety of existing applications with heterogeneous resource and performance requirements and sufficient flexibility and agility to dynamically adapt to future needs. The NAI project should go further than traditional objectives like throughput, execution speed, latency, or object connection density and enable the effective integration of a multitude of new technologies. This should include technologies for the physical layer (reconfigurable intelligent surfaces) , 3D transition (NTN - non-terrestrial networks), and architectural principles (like slicing and dynamic end-to-end orchestration). The project will promote the emergence of new applications and services thanks to transparency in terms of performance, robustness, and user security. The project will also put forward and implement interfaces with convergent network-cloud-sensing systems, offering a rich level of transparency to application developers , ranging from the edge to the cloud, from connected mini-objects to large data centres through multi-access edge computing (MEC).
- Role of the DIANA team: Supervise two PhDs to start during 2024. The first one on monitoring plane for mobile cellular networks and the second on experimental evaluation of sliced cellular networks.

9.3.3 PC10, NF FPNG : French network of test platforms for new-generation mobile communications

- Coordinator: Raymond Knopp, Eurecom
- Inria teams participating to the project : DIANA, Maracas.
- Summary: Setting up national-scale research infrastructures to test new hardware components for 5G and future networks and evaluate the paradigms of next-generation telecommunications networks. The targeted FPNG project is dedicated to setting up nationwide research infrastructures to test new hardware components for 5G and evaluate paradigms for the next generation of telecommunications networks. These research infrastructures will target basic technological components and also end-to-end network testing. This programme of platforms aims to work with all the important technologies in this area - from elementary electronic components to large-scale networking experiments - to provide responses to all the specific challenges defined by the Networks of the Future PEPR project. FPNG’s aim is firstly to structure this set of infrastructures and provide free access to existing infrastructures for the national group of PEPR researchers. Its second aim is to invest in new strategic and advanced infrastructures required to respond to the many challenges of the future.

- Role of the DIANA team: participating in the definition and deployment of the infrastructure. Our team has funding designated for acquiring necessary hardware equipment and engaging one DevOps engineer.

9.4 Université Côte d'Azur funded initiatives

The objective of the WEMON project funded in 2023 by the Academy of Excellence "Networks, Information, and Digital Society" of Université Côte d'Azur is to develop a data-driven light-weight solution for network monitoring and diagnostics, a solution able to estimate the performance of the network, both mobile and fixed, and troubleshoot it in case of service degradation, by solely relying on measurement data freely available within the browser. The activity on WEMON started in 2023 with the internship of Naomi Krimi from MIT and will continue in 2024 around a new PostDoc. This project is in collaboration with the Ermine Team of Inria centre at University of Rennes.

Participants: Chadi Barakat, Walid Dabbous, Arnaud Legout, Thierry Turletti, Damien Saucez.

10 Dissemination

10.1 Promoting scientific activities

- Chadi Barakat is on the editorial board of the Computer Networks journal, and is/was on the Technical Program Committee for the ACM Internet Measurement Conference 2024, the Network Traffic Measurement and Analysis conference (TMA 2024 and TMA 2023), the ACM MobiArch Workshop 2023, the International Teletraffic Congress (ITC 35) and the Mediterranean Communication and Computer Networking Conference (MedComNet 2023). He is currently in charge of international affairs at Inria centre at Université Côte d'Azur and member of the organizing committee for the Forum Numerica seminars of EUR DS4H.
- Walid Dabbous is Director of the Academy of Excellence RISE (Networks, Information and Digital Society). He is also member of the scientific committee of the DS4H Graduate school and member of the Ubinet International Master program steering committee. He was also member of the INRIA Evaluation Committee until August 2023. He served as a external evaluator for one of the ERC panels.
- Arnaud Legout is member of the expert committee for the NPI Model since April 2023. He served as external reviewer projet LeukocloTe for ERA-NET CHIST-ERA.
- Damien Saucez organized a hands-on session at the second SLICES-SC summer school in OULU, where approximately 50 participants deployed the SLICES blueprint on various testbeds using automation tools he developed. He served as the co-chair of the Artefact Evaluation Committee (AEC) for SIGCOMM 2023 and as a committee member for AEC at CONEXT 2023, advocating for research reproducibility. Damien also contributed as a Technical Program Committee (TPC) member for WNS3'2023.
- Thierry Turletti is on the editorial board of the Wireless Networks journal, and is/was on the Technical Program Committee for the IEEE International Conference on Communications (ICC 2024 and 2023), the IEEE/IFIP Network Operations and Management Symposium (NOMS 2024 and 2023), the 18th Workshop on Mobility in the Evolving Internet Architecture (MobiArch 2023), and the Workshop on ns-3 (WNS3 2024 and 2023).

10.2 Teaching - Supervision - Juries

10.2.1 Teaching

- Master 2 Ubinet: Chadi Barakat and Walid Dabbous, Evolving Internet, 31.5 hours, M2, Université Côte d'Azur, France.
- Master 2 Ubinet: Chadi Barakat and Walid Dabbous, Internet Measurements and New Architectures, 31.5 hours, M2, Université Côte d'Azur, France.
- Master 1 in Computer Science: Chadi Barakat, Computer Networks, 15 hours, M1, Université Côte d'Azur, France.
- Master 1 in Computer Science: Chadi Barakat, Internet of the future, 15 hours, M1, Université Côte d'Azur, France.
- Master 2 Estel: Chadi Barakat, Voice over IP, 9 hours, Université Côte d'Azur, France.
- Master Ubinet: Arnaud Legout, From BitTorrent to Privacy, 22.5 hours, M2, Université Côte d'Azur, France.
- Master module AWARE (Awareness-Raising to research) : Arnaud Legout, lecture 2 hours, Eurecom, France.
- Thierry Parmentelat helps coordinating the CS courses for the first year students of École des Mines de Paris, covering general topics like Numerical Programming with Python, Advanced Python Programming, and Introduction to Web technologies.

10.2.2 Supervision

PhD Students

- PhD in progress: Bernard Tamba Sandouno works on a "Geolocation assessment model of mobile network performance". His PhD is co-supervised by Chadi Barakat, Thierry Turletti and Walid Dabbous from the Diana team, and by Yamen Alsaba from YDATA. His thesis is funded by a CIFRE grant in collaboration with YDATA.
- PhD defended: Houssam Elbouanani finished his PhD on "Introducing Fidelity into Network Emulation" in March 2023. He was co-supervised by Chadi Barakat, Thierry Turletti and Walid Dabbous from the Diana team and funded by the Fed4Fire+ H2020 project.

Visiting PhD Students

- Harikrishna Kuttivelil:
 - From Sept. 2022 until Mar 2023
 - Institution: University of California, Santa Cruz, USA.
 - Subject: Community-structured decentralized learning
 - Supervisor: Thierry Turletti

Master Students

- Kaoutar Chiboub
 - From Mar. until Aug. 2023
 - Ubinet Master, Université Côte d'Azur
 - Subject: Deployment of a 5G infrastructure platform - SLICES REST backend & light federation
 - Supervisor: Damien Saucez

- Anass Dahchour
 - From Mar. until Aug. 2023
 - Ubinet Master, Université Côte d'Azur
 - Subject: A 5G Infrastructures Platform: Deployment, Automation, and CI/CD
 - Supervisor: Damien Saucez
- Nadia El Oumrassi
 - From Mar. until Aug. 2023
 - Ubinet Master, Université Côte d'Azur
 - Subject: Performance evaluation of Aether in open cellular networks
 - Supervisor: Damien Saucez
- Giovanni Pantaleo
 - From Mar. until Aug. 2023
 - Ubinet Master, Université Côte d'Azur
 - Subject: Monitoring mobile edge networks
 - Supervisors: Chadi Barakat and Thierry Turletti
- Yacoub Yacoub
 - From Mar. until Aug. 2023
 - Ubinet Master, Université Côte d'Azur
 - Subject: A digital twin for intelligent surfaces aided cellular network infrastructures
 - Supervisors: Damien Saucez, Chadi Barakat and Thierry Turletti
- Stefano Lioce
 - From May until Oct 2023
 - Politecnico di Bari
 - Subject: A system-level model for communication assisted by intelligent reflective surfaces in millimeter-wave.
 - Supervisors: Damien Saucez and Walid Dabbous

MIT Students

- Deniz Sertz
 - From June until Aug. 2023
 - Subject: Detecting and analyzing market manipulation on Bitcoin
 - Supervisor: Arnaud Legout
- Naomi Kirimi
 - From July until Sept. 2023
 - Subject: Leveraging Web browsing performance data for Network monitoring: A data-driven approach
 - Supervisor: Chadi Barakat

10.2.3 Juries

- Chadi Barakat served as reviewer of Ziad Tlaiss's PhD thesis "Automated network packet traces analysis methods for fault recognition and TCP flavor identification", defended in December 2023 at Mines-Telecom Atlantique Bretagne.
- Chadi Barakat served as reviewer of Philippe Graff's PhD thesis "Characterization, in-network identification and optimization of low-latency traffic transport - the case of Cloud-Gaming", defended in December 2023 at Université de Lorraine.
- Chadi Barakat served as reviewer of Matthieu Gouel's PhD thesis "Internet-Scale Route Tracing Capture and Analysis", defended in June 2023 at LIP6, Sorbonne Université.
- Chadi Barakat served as jury member for the mid-term review of David Baldassin's PhD thesis "Design and Evaluation of New Transport Protocols for WebRTC", Université Côte d'Azur and Cosmo Softwar, held in May 2023.
- Chadi Barakat served as jury member for the mid-term review of Ilias Driouich's PhD thesis "Privacy-Preserving Algorithms for Federated Learning", Inria, Université Côte d'Azur and Amadeus, held in May 2023.
- Chadi Barakat served as reviewer of Thomas Faval's PhD thesis "Strengthening Privacy and Cybersecurity through Anonymization and Big Data" defended in January 2023 at Politecnico di Torino.
- Chadi Barakat served as reviewer of Hina Qayyum's PhD thesis "Exposing misconduct on free online platforms: A study of mobile apps, web games, and social networks", validated in December 2023 at Macquarie University, Australia.
- Walid Dabbous served as member of the first year PhD monitoring committee (CSI) for Anderson Lourenço de Araujo at Université Côte d'Azur.
- Arnaud Legout served as jury member for the Ph.D. thesis defense of Rafael Ramos Tubino on 12 december 2023, LIRIS, Lyon 1.
- Thierry Turletti served as reviewer of Mukhtiar Bano's PhD thesis "A Robust Routing Architecture for Hybrid Software Defined and Wireless Mesh Networks", defended in March 2023 at Capital University of Science and Technology, Islamabad, Pakistan.
- Thierry Turletti served as reviewer of Matthews Jose's PhD thesis "In-network real-value computation on programmable switches", defended in March 2023 at Université de Lorraine, LORIA.
- Thierry Turletti served as reviewer of Sagar Arora's PhD thesis "Cloud Native Network Slice Orchestration in 5G and Beyond", in October 2023 at Sorbonne Université en Sciences, EURECOM.

10.3 Popularization

Damien Saucez is chargé de mission médiation scientifique interne. The role is to promote and favor scientific exchanges between Sophia's center researchers but also to popularize sciences within the center, not only for the researchers but for all personnel of the center. In 2023 we decided to joint the effort of science popularization with Terra Numerica to enlarge the reach of our activities to a larger public. A concrete example is that starting from November, we organize scientific conferences for the public every last Tuesday of the month in Terra Numerica premises to open to the world in addition to activities ongoing within Inria premises.

Within Inria, the two main activities that are put in place are the so-called In'tro and Café In.

The concept of In'Tro has been proposed by Fabien Gandon and we implemented it successfully in March 2021. In'Tro aims to promote recently hired researcher in order to foster new collaborations. Every month, a researcher is allocated a slot of 30 minutes during lunch time to presents her/his work during 15 minutes and to answer questions during 15 minutes. In 2023, we moved forward and now In'Tro sessions are integrated in the CEP to give additional visibility to the sessions.

The Café-In events are different in their objective and organized since 2012. Once a month a one hour slot is dedicated to popularize sciences to Inria personnel, regardless of whether they are scientific or not. After lunch, a researcher, or a panel of researchers, is invited to talk about a subject of his/her choice around a coffee. The main objective is not to foster new collaborations but to allow everyone at Inria to understand important research subjects that are worked on by Inria researchers and to open their curiosity.

For more information, check the [Inria intranet](#) and [Terra Numerica website](#).

10.3.1 Internal or external Inria responsibilities

DIANA team members actively engage in hosting week-long internships for students at the 3rd level, primarily by introducing them to the state-of-the-art R2lab anechoic chamber. Additionally, they provide insightful explanations of electromagnetic wave transmission in simplified terms, ensuring a comprehensive understanding for the interns.

10.3.2 Interventions

As part of his responsibilities in scientific mediation, Damien Saucez orchestrates visits for the DIANA team researchers, and more broadly, for researchers from the Inria center to high school classes as part of the CHICHE program. Although two scheduled participations by Walid Dabbous and Manel Khalefi were initially planned for 2023, they have been postponed to early 2024 due to scheduling constraints.

11 Scientific production

11.1 Major publications

- [1] O. Belmoukadam and C. Barakat. ‘Unveiling the end-user viewport resolution from encrypted video traces’. In: *IEEE Transactions on Network and Service Management* 18.3 (Sept. 2021), pp. 3324–3335. DOI: [10.1109/TNSM.2021.3083070](https://doi.org/10.1109/TNSM.2021.3083070). URL: <https://hal.inria.fr/hal-03230168>.
- [2] F. De Pellegrini, L. Maggi, A. Massaro, D. Saucez, J. Leguay and E. Altman. ‘Blind, Adaptive and Robust Flow Segmentation in Datacenters’. In: *INFOCOM 2018 - IEEE International Conference on Computer Communications*. Honolulu, United States, Apr. 2018. URL: <https://hal.inria.fr/hal-01666905>.
- [3] M. Flittner, M. N. Mahfoudi, D. Saucez, M. Wählisch, L. Iannone, V. Bajpai and A. Afanasyev. ‘A Survey on Artifacts from CoNEXT, ICN, IMC, and SIGCOMM Conferences in 2017’. In: *Computer Communication Review* 48.1 (Apr. 2018), pp. 75–80. URL: <https://hal.inria.fr/hal-01968401>.
- [4] M. Gabelkov, A. Ramachandran, A. Chaintreau and A. Legout. ‘Social Clicks: What and Who Gets Read on Twitter?’. In: *ACM SIGMETRICS / IFIP Performance 2016*. Antibes Juan-les-Pins, France, June 2016. URL: <https://hal.inria.fr/hal-01281190>.
- [5] M. J. Khokhar, N. A. Saber, T. Spetebroot and C. Barakat. ‘An Intelligent Sampling Framework for Controlled Experimentation and QoE Modeling’. In: *Computer Networks* 147 (Dec. 2018), pp. 246–261. DOI: [10.1016/j.comnet.2018.10.011](https://doi.org/10.1016/j.comnet.2018.10.011). URL: <https://hal.inria.fr/hal-01906145>.
- [6] M. N. Mahfoudi, T. Parmentelat, T. Turletti, W. Dabbous and R. Knopp. *Deploy a 5G network in less than 5 minutes: Demo Abstract*. ACM SIGCOMM Posters and Demos. Poster. Aug. 2017. URL: <https://hal.inria.fr/hal-01580065>.
- [7] M. N. Mahfoudi, G. Sivados, O. Bensouda Korachi, T. Turletti and W. Dabbous. ‘Joint range extension and localization for LPWAN’. In: *Internet Technology Letters* (June 2019). DOI: [10.1002/itl2.120](https://doi.org/10.1002/itl2.120). URL: <https://hal.archives-ouvertes.fr/hal-02170466>.
- [8] D. Saucez, L. Iannone, C. Albert and F. Coras. *Locator/ID Separation Protocol (LISP) Impact*. Internet Engineering Task Force (IETF), Request for Comments: 7834. Apr. 2016. URL: <https://hal.inria.fr/hal-01423163>.

- [9] H. Soni, W. Dabbous, T. Turetletti and H. Asaeda. ‘NFV-based Scalable Guaranteed-Bandwidth Multicast Service for Software Defined ISP networks’. In: *IEEE Transactions on Network and Service Management* 14.4 (Dec. 2017), p. 14. DOI: [10.1109/TNSM.2017.2759167](https://doi.org/10.1109/TNSM.2017.2759167). URL: <https://hal.inria.fr/hal-01596488>.
- [10] L. Vigneri, T. Spyropoulos and C. Barakat. ‘Low Cost Video Streaming through Mobile Edge Caching: Modelling and Optimization’. In: *IEEE Transactions on Mobile Computing* (2018). DOI: [10.1109/TMC.2018.2861005](https://doi.org/10.1109/TMC.2018.2861005). URL: <https://hal.inria.fr/hal-01855304>.

11.2 Publications of the year

International journals

- [11] H. Elbouanani, C. Barakat, W. Dabbous and T. Turetletti. ‘Troubleshooting Distributed Network Emulation’. In: *Annals of Telecommunications - annales des télécommunications* (2024). URL: <https://inria.hal.science/hal-04373896>.
- [12] B. Tamba Sandouno, Y. Alsaba, C. Barakat, W. Dabbous and T. Turetletti. ‘A novel approach for ray tracing optimization in wireless communication’. In: *Computer Communications* 209.1 (2023), pp. 309–319. DOI: [10.1016/j.comcom.2023.07.016](https://doi.org/10.1016/j.comcom.2023.07.016). URL: <https://inria.hal.science/hal-04157758>.

International peer-reviewed conferences

- [13] H. Elbouanani, C. Barakat, W. Dabbous and T. Turetletti. ‘Delay-based Fidelity Monitoring of Distributed Network Emulation’. In: COMSNETS 2023 :TASIR Workshop - 15th International Conference on COMMunication Systems & NETworkS : Testbeds for Advanced Systems Implementation and Research. 2023 15th International Conference on COMMunication Systems & NETworkS (COMSNETS). Bangalore, India, 8th Jan. 2023. DOI: [10.1109/COMSNETS56262.2023.10041407](https://doi.org/10.1109/COMSNETS56262.2023.10041407). URL: <https://inria.hal.science/hal-03909929>.
- [14] H. Elbouanani, C. Barakat, W. Dabbous and T. Turetletti. ‘Troubleshooting Distributed Network Emulation’. In: ICIN 2023 - 26th Conference on Innovation in Clouds, Internet and Networks. 2023 26th Conference on Innovation in Clouds, Internet and Networks and Workshops (ICIN). Paris, France, 7th Mar. 2023. DOI: [10.1109/ICIN56760.2023.10073480](https://doi.org/10.1109/ICIN56760.2023.10073480). URL: <https://inria.hal.science/hal-03962530>.
- [15] R. U. Mustafa, C. Barakat and C. E. Rothenberg. ‘YouTube goes 5G: QoE Benchmarking and ML-based Stall Prediction’. In: IEEE Wireless Communications and Networking Conference (WCNC). Dubai, United Arab Emirates, 21st Apr. 2024. URL: <https://inria.hal.science/hal-04400816>.
- [16] B. Tamba Sandouno, Y. Alsaba, C. Barakat, W. Dabbous and T. Turetletti. ‘A Novel Approach to Mobile Outdoor QoS Map Generation’. In: *IEEE Conference on Wireless Communications and Networking*. WCNC 2023 - IEEE Wireless Communications and Networking Conference. Glasgow, Scotland, United Kingdom, 26th Mar. 2023. DOI: [10.1109/WCNC55385.2023.10118977](https://doi.org/10.1109/WCNC55385.2023.10118977). URL: <https://inria.hal.science/hal-03932145>.

Doctoral dissertations and habilitation theses

- [17] H. Elbouanani. ‘Introducing fidelity into network emulation’. Université Côte d’Azur, 2nd Mar. 2023. URL: <https://theses.hal.science/tel-04194461>.