RESEARCH CENTRE

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

# 2024 ACTIVITY REPORT

# Project-Team DIANA

## Design, Implementation and Analysis of Networking Architectures

**DOMAIN**

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

**THEME**

**Networks and Telecommunications**

Inria

# Contents

# 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

## Research Scientists

- Walid Dabbous [Team leader, INRIA, Senior Researcher]
- Chadi Barakat [INRIA, Senior Researcher]
- Arnaud Legout [INRIA, Senior Researcher]
- Katia Obraczka [INRIA, Senior Researcher, from Oct 2024 until Oct 2024]
- Damien Saucez [INRIA, Researcher]
- Thierry Turletti [INRIA, Senior Researcher]

## Post-Doctoral Fellows

- Sanaa Ghandi [UNIV COTE D'AZUR]
- Manel Khelifi [INRIA]

## PhD Students

- Yassir Amami [INRIA, from Oct 2024]
- Stefano Lioce [INRIA, from Feb 2024]
- Bernard Tamba Sandouno [Y-DATA, CIFRE, until Jul 2024]
- Mohammadbagher Tavassoli Kejani [INRIA, from Jun 2024]

## Technical Staff

- Thierry Parmentelat [INRIA, Engineer]

## Interns and Apprentices

- Yassir Amami [INRIA, Intern, from Mar 2024 until Aug 2024]
- Mattia Ciaccia [INRIA, Intern, from Mar 2024 until Aug 2024]
- Mohamed El Khatib [INRIA, Intern, from Mar 2024 until Aug 2024]
- Khalid Hachem [INRIA, Intern, from Mar 2024 until Aug 2024]
- Maryam Tamlalti [INRIA, Intern, from Apr 2024 until Aug 2024]
- Saadeddine Tazili [INRIA, Intern, from Mar 2024 until Aug 2024]

## Administrative Assistant

- Christine Foggia [INRIA]

## External Collaborator

- Nathalie Currid [UNIV COTE D'AZUR, Project Manager, RISE Academy]

# 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 our research, we follow an **experimental approach** in which the scientific evaluation of proposed solutions should be done in both controlled and realistic environments before deployment. In this context, reproducibility is key in designing networked systems and evaluating their performance in particular in highly variable wireless access networks.

In the DIANA project-team, we pursue three main research directions: (i) designing and deploying a measurement plane providing **network service transparency**, (ii) designing mechanisms for enhanced **programmable software networks**, and (iii) proposing tools and mechanisms for **network experimentation reproducibility**. These three points are detailed in the next section.

# 3 Research program

## 3.1 Network Service Transparency

Network Service Transparency is about providing 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. Service transparency therefore means to provide information meaningful to users and application developers, in terms of high-level indicators such as quality of experience (QoE), or related to societal interests of the user as a "connected citizen" (e.g. possible violation of network neutrality, opinion manipulation, etc), rather than network-level metrics such as available bandwidth, loss rate, delay or jitter. The Internet's best-effort routing service simplicity, that comes with no guarantee in terms of quality of service (QoS), has been instrumental to its huge success, but unfortunately at the expense of a variable quality at the access. Despite considerable efforts done by operators and content providers to optimize the Internet content delivery chain, 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 even harder to predict. The trend with modern apps, designed for mobile terminals, seems to exacerbate the difficulty, as they tend to focus on simpler interfaces and lesser control on the network. 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 and to infer the behavior of the application. This is however a complex task as the traffic might be obfuscated or encrypted. Our objectives in this research direction are to come up with tools that improve transparency, and privacy awareness. The proposed measurements techniques should adapt to the network architectural changes; deployment could be done either as an overlay, or by exploiting in-network functionalities as provided in 5G networks. The ultimate goal is to have measurements as native functionality in future network architecture.

### 3.2 Programmable Software Networks

The tremendous growth of demand for high-definition and personalized multimedia content places significant strain on the network's capacity, particularly for mobile networks. As a complement to network service transparency as mentioned above, network programmability allows to control traffic with a very high precision at large scale. It is important to leverage network programmability, efficient data dissemination mechanisms, and QoE modeling with the objective to better utilize network resources, and thus improve QoE. The general idea being that it is not always necessary to use the shortest, fastest, most stable paths to reach the highest quality of experience, which means that we can use detours, thus freeing direct paths for traffic requiring very high performance. It is worth noticing that carrying more traffic on a given network means having less margin in case of network faults. It is therefore important to work on fault-tolerant techniques in programmable networks. It is therefore important to work on algorithms that improve the dynamic placement, migration, and scaling up or down, of Virtual Network Functions (VNFs) in order to accommodate for resource availability and demand, heterogeneity, and mobility of users, so as to support applications with stringent demands such as e.g. ultra-high-definition video streaming. This includes fault management mechanisms, with controller-hosted algorithms that react quickly in case of link failures or network partitioning, and reprogram switches accordingly, so as to achieve maximal resilience of the data plane. It is also important to extend this thread of work to more specific areas, namely 5G Radio Access Networks, Intelligent Transport Systems (ITS) and industrial networks, that each has exhibited specific constraints, service requirement, and related challenges. This move requires to rely on Software Defined Networking (SDN) that enables a programmatic approach to networking, hence offering modularity and flexibility. The challenge with SDN is to be able to certify the behavior of the system while keeping the solution generic.

### 3.3 Network Experimentation Reproducibility

Network Experimentation Reproducibility is key for research activities that study networking systems in general, and wireless systems in particular, particularly when it comes to performance assessment. Ensuring scientifically sound, and thus reproducible, evaluation of such systems is time-consuming as it requires simulation, emulation and controlled experimentation tools, together with rigorous methodology. The DIANA project-team has a long tradition in this domain, building tools and methods, that in turn allow us to advocate reproducible research.

### 3.4 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 behaviors.
- 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 (5G and beyond)
- Realistic simulations and reproducible experiments

# 5 Social and environmental responsibility

## 5.1 Socio-economic impact of research results

Over the past decade, networks have undergone a major transformation, marked by a clear shift from specialized hardware to software-based solutions running on affordable, generic infrastructures. This evolution has extended to cellular operator networks, both at the radio access and core network levels. Mastering this approach, known as "disaggregated radio networks," is crucial for France and Europe to maintain their sovereignty in the critical domain of future networks. This trend was confirmed by the publication of a manifesto by European operators in 2021. However, significant challenges remain: how to ensure high-throughput performance for software functions, how to maintain system reliability despite the complexity of interdependencies in software stacks, how to meet real-time constraints within a virtualized wireless network ? The availability of a large-scale digital infrastructure for testing and validating solutions before deployment is of critical importance.

With respect to theses challenges, our project team has played a key role in advancing SLICES-RI, contributing significantly to the design and deployment of SophiaNode, a platform jointly managed by Inria Sophia Antipolis and Eurecom. We have also led efforts to define and implement the SLICES Post-5G Blueprint and collaborated with European and American colleagues from the O-RAN initiative. Finally, we are about to engage in the upcoming DIGITAfrica project, which aims to develop a pan-African digital research infrastructure.

## 5.2 Non-Pharmacological Interventions (NPIs) Evaluation Model

We are working on two projects with significant societal impacts, The first one is on the definition of Non-Pharmacological Interventions evaluation model. This initiative aims to establish a standard framework for evaluating NPIs in healthcare, enhancing research quality, result comparability, and broader adoption in healthcare systems. Supported by 36 scientific societies and 14 French health authorities, it was presented at the French Senate in 2023 and is being developed at the European level for international adoption.

## 5.3 Greasy

This other initiative examines the persistence of cookies, revealing that users can still be tracked despite blocking or deleting cookies. It highlights how the advertising industry uses advanced tracking techniques to circumvent browser restrictions on third-party cookies. Findings from the project were presented at PrivacyCon21, hosted by the Federal Trade Commission, and received widespread media coverage in outlets like Le Monde and Techniques de l'ingénieur.

# 6 Highlights of the year

This year, our project team's dedicated efforts have positioned SophiaNode as a flagship site for the SLICES-RI initiative. It stands as the first site to fully implement the SLICES Post-5G blueprint. Since its transition to the pre-operational phase on November 11th, 2024, SophiaNode has become a cornerstone in the deployment of SLICES-RI. For more details, visit the The SLICES-RI website and explore the Post-5G Blueprint documentation.

# 7 New software, platforms, open data

## 7.1 New software

### 7.1.1 ElectroSmart

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

**Functional Description:** The adoption of wireless technologies has surged in recent years with the widespread use of Wi-Fi, Bluetooth, and cellular technologies ranging from 2G to 5G. However, the health impact of exposure to radiofrequency waves remains poorly understood and concerning (ANSES, March 2018, The Lancet, June 2011). Consequently, the Council of Europe advocates for an exposure minimization approach guided by the principle ALARA (as low as reasonably achievable). Unfortunately, both the general public and authorities have lacked tools to measure exposure to radiofrequency waves effectively.

In 2015, Arnaud Legout applied his expertise in instrumentation and experimentation to launch the project ElectroSmart with two main goals: i) to provide a scientifically validated public tool for measuring exposure to radiofrequency waves, and ii) to map the global evolution of radiofrequency wave exposure. ElectroSmart is based on a crowdsourcing Android application that enables users to measure and collect data on their radio environment, complemented by a calibration process for measurements [TIM21] to ensure exposure data quality. The 9.8 billion of measurements collected in 150 countries over six years enabled the creation of the first global map of radiofrequency exposure evolution, which we published in the journal Environment International [EI2022].

As of September 3, 2024, the application had been downloaded 2,456,757 times, with 173,328 active users and a rating of 4.5/5. Notably, due to Android's refusal to provide reasonable support for 5G exposure data and the increasing challenges of maintaining the application in the long term, we officially ceased maintenance of the Android app in October 2022 after more than six years of development and maintenance. At that time, we made the code fully open source under the BSD 3-Clause license and available on GitHub. As of September 3, 2024, the GitHub project had received 35 stars and had been forked 12 times. ElectroSmart was removed from the *Play Store* by Google in August 2024 following the end of its maintenance.

**News of the Year:** As of September 3, 2024, the application had been downloaded 2,456,757 times, with 173,328 active users and a rating of 4.5/5. Notably, due to Android's refusal to provide reasonable support for 5G exposure data and the increasing challenges of maintaining the application in the long term, we officially ceased maintenance of the Android app in October 2022 after more than six years of development and maintenance. At that time, we made the code fully open source under the BSD 3-Clause license and available on GitHub. As of September 3, 2024, the GitHub project had received 35 stars and had been forked 12 times. ElectroSmart was removed from the *Play Store* by Google in August 2024 following the end of its maintenance.

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

**Contact:** Arnaud Legout

**Participant:** Arnaud Legout

### 7.1.2 nepi-ng

**Keywords:** Wireless network, Experimentation

**Functional Description:** Experimentation is an essential step for realistic evaluation of wireless network protocols. `nepi-ng` leverages job oriented programming model, and efficient single-thread execution of parallel programs using Python's asynchronous programming paradigm (`asyncio`) to provide an efficient and modular fine-grained synchronization mechanism for networking experiments, with a light software dependency footprint. `nepi-ng` has been designed with the ambition

to address the challenges of (1) efficiency: removing all possible overhead, even when an experiment is remotely controlled over several ssh hops, (2) light software dependency footprint: keeping the overall software dependencies to a strict minimum, so that the approach can be applicable in a wide variety of contexts and testbeds, and (3) modularity: allowing pieces of code to be re-used or shared.

**URL:** https://nepi-ng.inria.fr

**Contact:** Thierry Parmentelat

#### 7.1.3 SLICES Post-5G Blueprint

**Name:** SLICES Post-5G Blueprint

**Keywords:** 5G protocols, Reproducibility, Evaluation platform

**Functional Description:** 5G's modular architecture bridges telecom and IT, fostering innovation in Post-5G research and providing a versatile framework for experimentation. However, deploying a complete 5G setup remains complex, requiring specialized expertise and significant resources, potentially diverting researchers from their core work. The SLICES Post-5G Blueprint addresses this by offering a modular, replicable framework of software, hardware, and methodologies, enabling full or partial deployments. Researchers can deploy only the 5G core, use a simulated RAN, or integrate multiple RANs with a core. The blueprint supports reproducible research through a step-by-step workflow and includes an open-source reference implementation using tools like OpenAirInterface, MinIO, FastAPI, kubernetes, and Ansible. Integrated into SLICES-RI, this framework simplifies Post-5G experimentation while promoting collaborative reproducible research.

**URL:** https://doc.slices-ri.eu/BlueprintServices/beyond5G/beyond5G.html

**Contact:** Damien Saucez

### 7.2 New platforms

**Participants:** Thierry Parmentelat, Thierry Turletti, Damien Saucez, Walid Dabbous.

#### 7.2.1 Reproducible research Lab - R2lab

The R2lab testbed has been operating 24/7 since early 2016. It has been used by more than 150 users, half of them from France and the other half from all over the world to evaluate a wide range of wireless networking scenarios in a realistic and reproducible environment (see usage statistics here). The facility remains stable with minimal disruptions, now supporting 5G and LoRa (from Long Range, a physical proprietary radio communication technique) devices. The focus is on leveraging our investments to advance reproducible research.

R2lab has been upgraded with advanced equipment, including Universal Software Radio Peripherals USRP N300 and N320 devices, connected via high-speed fiber to the SophiaNode cluster, and AW2S 5G Remote Radio Units offering enhanced capabilities for MIMO (Multiple Input Multiple Output) configurations. Recent software developments have focused on supporting Docker images alongside metal-based formats for images, enabling experimenters to use off-the-shelf OAI (Open Air Interface) images, as well as mainstream tools for building images.

R2lab is in the process of being integrated into the SLICES-RI infrastructure [5] via the SophiaNode. To ensure reproducibility of previous experiments conducted in R2lab, the existing equipment will remain accessible through the R2lab workflows while also being compatible with the SLICES-RI workflow. In contrast, new equipment will be exclusively used within the SLICES-RI workflow. In other words, the evolution of R2lab is designed to be backward compatible.

#### 7.2.2 SophiaNode: an open programmable 5G platform

The advent of 5G has blurred the lines between wireless and wired networks, cloud computing, and data management. To support Post-5G experimentation, R2lab is being expanded to incorporate programmable networking, cloud resources, and high-performance real-time processing at scale. This evolution, called the SophiaNode, is a SLICES-RI site developed in collaboration with Eurecom. The SophiaNode comprises three wireless facilities: the R2lab anechoic chamber at Inria augmented with 5G hardware, an indoor site at Eurecom, and an outdoor site on the SophiaTech campus. These facilities are interconnected via high-speed fiber links (600 Gbps as of this writing) to a data center at Inria, which hosts compute resources ($1500^+$ cores, $3^+$ TB RAM), storage (planned $250^+$ TiB), and hardware accelerators like GPUs and SmartNICs.

This year, significant efforts have established SophiaNode as a reference site for the SLICES-RI project. It is the first site to fully implement the SLICES Post-5G blueprint. Since entering its pre-operation phase on November 11th, 2024, the SophiaNode has become a cornerstone of the SLICES-RI deployment.

### 7.3 Open data

Our project-team has been engaged in reproducible experiments for over a decade. We promote the publication and sharing of experiment scripts, scenarios, and results. These datasets are invaluable for researchers looking to replicate or expand upon the experiments. To support this, we have developed tools for experiment replication, such as `nepi-ng` in RL2ab and participated in the effort on the Plain Orchestrating Service (Pos) [14] in the context of SLICES-RI. Additionally, we have contributed to defining experiment descriptions, results metadata, and implementing the metadata registry systems (MRS) within the SLICES project.

The Twitter dataset, encompassing the complete Twitter social graph collected in 2012, continues to be sought after by researchers. Between 2021 and 2024, we shared this dataset with researchers on four occasions.

Regarding the 9.8 billion measurements collected by the ElectroSmart application, we chose not to make them publicly available. On one hand, doing so would have required extensive anonymization efforts, and on the other, there was an ongoing project to launch a startup aimed at leveraging this data.

## 8 New results

### 8.1 Network Service Transparency

#### 8.1.1 Leveraging Web browsing performance data for Network monitoring

**Participants:** Chadi Barakat, Sanaa Ghandi.

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 [12] in 2023, and part of the WEMON project funded by the Academy of Excellence "Networks, Information, and Digital Society" of Université Côte d'Azur. Within this project Sanaa Ghandi joined the Diana team as a post-doctoral researcher in 2024 and worked 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.

#### 8.1.2 Efficient coverage maps for mobile networks

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

We worked on large-scale cartography of wireless network performance, covering areas such as cities, regions, or even entire countries, with the aim of improving network transparency and informing end-users about cellular network coverage based on their location. Unlike existing solutions that rely on measurements or statistical models, we adopted a more accurate and deterministic approach leveraging Ray Tracing to simulate wave propagation and capture interactions with environmental obstacles, such as reflection and refraction. By modeling waves as rays emitted from antennas according to their lobes, Ray Tracing calculates intersections with 3D obstacles and determines new ray directions after these interactions, continuing the process until the receiver is either reached (indicating coverage) or not (indicating lack of coverage). Although this method offers high accuracy, it comes with significant computational and memory demands due to complex processes like ray generation and the exhaustive reception tests needed to produce coverage maps for a large number of receivers. In collaboration with ZoneADSL & Fibre, as part of Bernard Tamba Sandouno's PhD research [16], we proposed targeted optimizations to generate precise signal power and download capacity maps on a large scale while significantly reducing computational overhead. Our work highlights the limitations of traditional methods and validates the effectiveness of our optimizations in dramatically reducing execution times without compromising accuracy. Specifically, we introduced an innovative ray generation technique that minimizes the number of rays launched from antennas by considering environmental factors, as opposed to the brute-force methods typically used. This site-specific approach, combined with a re-engineered reception test process, achieved a remarkable 1200-fold reduction in Ray Tracing execution time for terrains with slight altitude variations. Extending these optimizations to more diverse terrains, we refined all Ray Tracing processes to improve signal power mapping efficiency [15, 7]. These advancements accelerated large-scale map generation by a factor of 50, demonstrating the adaptability and efficiency of our methods across varied environments. The results of this work are detailed in Bernard's PhD thesis [16].

#### 8.1.3 Troubleshooting distributed network emulation

**Participants:** Houssam Elbouanani, Chadi Barakat, Walid Dabbous, Thierry Turletti.

We worked on improving the transparency of virtualized network environments, in particular a Mininet-like network, where a virtual network is mapped over a physical infrastructure. The problem of these networks is that their performance strongly depends on how well the underlying physical infrastructure is dimensioned. Any lack of resources in the underlying infrastructure results in a violation of the performance guarantees offered to the virtual network, a violation that is challenging to detect and troubleshoot. Throughout the PhD thesis of Houssam El Bouanani defended last year, we worked on this problem and contributed with a new framework based on network delay measurements in the virtual network that, by comparing the delay measurements to their reference values, infer if the virtualization is working properly or not [9], and if not the case, identify the part of the infrastructure that is faulty with the help of network tomography techniques [10]. The two articles cited hereabove were published in 2024.

#### 8.1.4 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 was published in WCNC 15 [13].

## 8.2 Programmable Software Networks

### 8.2.1 Next-Generation Intelligent Transportation Systems

**Participants:** Katia Obraczka, Thierry Turletti.

In the context of the DrIVE associate team, we had made the following contributions related to next generation Intelligent Transportation Systems (ITS). ITS include a variety of services and applications such as road traffic management, traveler information systems, public transit system management, and autonomous vehicles. It is expected that ITS will be an integral part of urban planning and future cities as it will contribute to improved road and traffic safety, transportation and transit efficiency, as well as to increased energy efficiency and reduced environmental pollution. However, ITS pose a variety of challenges due to its scalability and diverse quality-of-service needs, as well as the massive amounts of data it will generate. We published a survey that explores the use of Machine Learning (ML), which has recently gained significant traction, to enable ITS [8]. We proposed a novel dynamic controller assignment algorithm targeting connected vehicle services and applications, also known as Internet of Vehicles (IoV). Our approach considers a hierarchically distributed control plane, decoupled from the data plane, and uses vehicle location and control traffic load to perform controller assignment dynamically. We modeled the dynamic controller assignment problem as a multi-agent Markov game and solved it with cooperative multi-agent deep reinforcement learning. Simulation results using real-world vehicle mobility traces showed that the proposed approach outperforms existing ones by reducing control delay as well as packet loss. This work has been published in the IEEE TNSM journal [24]. We then leveraged 5G Unmanned Aerial Vehicles (UAVs) to enhance network resource allocation among vehicles by positioning UAVs on-demand as "flying communication infrastructure". We proposed a deep reinforcement learning (DRL) approach to determine the position of UAVs in order to improve the fairness and efficiency of network resource allocation while considering the UAVs' flying range, communication range, and limited energy resources. We used a parametric fairness function for resource allocation that can be tuned to reach different allocation objectives ranging from maximizing the total throughput of vehicles, maximizing minimum throughput, as well as achieving proportional bandwidth allocation. Our simulation results showed that the proposed DRL approach to UAV positioning can help improve network resource allocation according to the targeted fairness objective. These results have been published in the IEEE Transactions on Network and Service Management journal [25]. In 2024, we proposed the Dynamic, Decentralized, Distributed, Delegation-based (D4) network control plane architecture which aims at providing adequate communication support for connected vehicles. To our knowledge, D4 is the first framework to support on-demand network control decentralization. We demonstrate the benefits of D4 through a proof-of-concept prototype running on a fully reproducible emulation platform. Experimental results using a variety of real-world scenarios demonstrate that D4 delivers lower latency with minimal additional overhead. This work has been published in the ACM journal on Autonomous Transportation Systems [11].

#### 8.2.2 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 contraints but also jitter and that are immune to vulnerabilities. This ongoing work is done in collaboration with the RESIST project-team at Inria Nancy and Aalborg University. The results of this work have been accepted for publication in NOMS'25 [19].

#### 8.2.3 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 (unique identifiers used to receive Bitcoin transactions) is still poorly understood. The goal of this project is to explore several key aspects and this graph. 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. The Bitcoin graph of addresses is a large graph with 1 billion addresses and 10 billion edges representing the financial transactions between the addresses. 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.

#### 8.2.4 RIS-aided communication

**Participants:** Damien Saucez, Walid Dabbous, Stefano Lioce.

Reconfigurable Intelligent Surfaces (RIS) are emerging as a transformative technology for the evolution of 5G and beyond wireless communication networks. These surfaces are composed of tunable metasurfaces containing hundreds of controllable elements, capable of dynamically manipulating electromagnetic waves by adjusting their reflection, propagation, and reconfiguration. RIS-assisted systems facilitate signal transmission in complex environments by intelligently redirecting signals toward their destinations, mitigating blockages, and reducing interference. As a result, they enhance network coverage, improve spectrum reliability, and increase energy efficiency. Despite significant advancements in RIS-assisted systems, comprehensive studies on their integration into future networks remain limited, particularly regarding the challenges of developing robust channel models. This research has focused on modeling the behavior of RIS-assisted communication in real network scenarios. One notable contribution involves exploring the relationship between circuit parameters—critical for representing the unit cells within metasurfaces and their reconfigurability circuits—and system-level parameters, to assess the overall performance of RIS-assisted communication. Another area of investigation addresses the impact of phase quantization on communication performance. We analyzed scenarios involving both continuous and quantized phase values, examining the effects of quantization while considering the influence of circuit components in RIS unit cells. A paper detailing the findings of this research has been accepted at the LASCAS symposium, in February 2025 [17].

#### 8.2.5 LISP standardization

**Participants:** Damien Saucez.

After several years of effort in the Internet Engineering Task Force IETF working groups on LISP standardization, three Request for Comments (RFCs) were published in 2022 : one informational track RFC on Locator/ID Separation Protocol (LISP) architecture and two standard track RFCs on LISP security protections and on inter-domain message exchanges. We are currently working on moving RFC8111 from the experimental category to the Standards Track [18].

### 8.3 Experimental Evaluation

#### 8.3.1 SLICES-RI Post-5G Blueprint

**Participants:** Damien Saucez, Thierry Turletti.

A significant scientific outcome of this research axis is the definition, implementation, and initial deployment of the SLICES-RI Post-5G blueprint. This blueprint fosters collaboration between engineers and non-engineers by creating a shared terminology and a consistent vision aligned with specific research objectives. It categorizes research in 5G and beyond into five distinct categories, each complementing the others.

At the top level, vertical service integration supports experimenters who use a 5G environment to transport their workloads without focusing on 5G research itself, treating 5G as a utility. The second category addresses researchers developing custom algorithms for network resource allocation, requiring access to the network control plane. Deeper layers involve researchers modifying the Medium Access Control (MAC) and physical layers, typically implemented in radio component firmware, necessitating privileged logical access to update hardware code. Another category includes researchers developing custom hardware, such as antennas or metasurfaces, which requires physical access to integrate new components into the infrastructure. Finally, the fifth category combines telecommunications and computational resources for studies such as cyber-system analysis and digital twin development to replicate real-world environments.

This clear classification of experiment categories helps identify the core requirements and building blocks necessary to support Post-5G research. Key elements include the ability to deploy custom 5G core networks and distributed Radio Access Networks, configurable and modifiable radio hardware, and unrestricted access to APIs for manipulating both control and user planes, as well as modifying codebases, firmware, and network settings. Additionally, the blueprint implementation must automatically collect experimental data and metadata, making it available to both users and the broader research community.

Based on these requirements, we have designed a fully adaptable, multi-site, multi-technology 5G environment. This environment enables researchers to select and customize specific components without needing to modify the rest of the system. A reference implementation of the blueprint has been developed and integrated into the SLICES-RI services portal. As of November 2024, the Post-5G blueprint service is in pre-operation within the SLICES-RI infrastructure. Further information on demonstrations and tutorials related to the post-5G blueprint can be found in [14, 20, 21, 22, 23].

## 9 Bilateral contracts and grants with industry

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

### 9.1 Bilateral contracts with industry

**Collaboration with YDATA** We had a collaboration with ZoneADSL & Fibre on the topic of geolocation assessment of mobile network performance. The activity was funded with a CIFRE contract. The PhD student Bernard Tamba Sandouno started his PhD on this topic on May 2021 and defended his thesis in June 2024. He developed a tool to efficiently compute coverage maps for mobile broadband networks using a ray tracing approach.

The budget allocated to the DIANA project-team includes 60 k€, supplemented by PhD funding of approximately 125 k€.

## 10 Partnerships and cooperations

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

### 10.1 International research visitors

#### 10.1.1 Visits of international scientists

**Inria International Chair** Professor Katia Obraczka has been awarded an Inria International Chair for the 2021-2025 period. The research program entitled: "Smart Networks: When Computational Intelligence and Networking Meet" will explore synergies between machine learning (ML) and networking domains by addressing two complementary goals: (1) Explore ML techniques as they apply to networks, their protocols, and their services towards intelligent network systems that are simple, automatically adapt to current conditions, do not require human in the loop, and deliver adequate end-to-end performance; and (2) Investigate how networking can benefit and empower ML. More specifically, as computing and storage shift to the edge of the network, this chair is interested in exploring how ML can leverage the network as a distributed, decentralized computing resource to handle the enormous amounts of data generated at the edge by providing full decentralization without compromising accuracy and preserving end user privacy. Prof Obraczka had realized up to now two visits to Inria, one in November 2022 and one in October 2024. In 2025, the collaboration will focus on enhancing network resilience to withstand natural disasters and malicious attacks.

### 10.2 European initiatives

#### 10.2.1 Horizon Europe

**CONVERGE**

- Title: Telecommunications and Computer Vision Convergence Tools for Research Infrastructures
- Duration: 36 months, (1/2/2023, 31/1/2026)
- Coordinator: INESC TEC
- Partners: 16 members including INESC TEC (Portugal), UOulu (Finland), ALLBESMART (Portugal), Greenerwave (France), Eurecom (France).
- Inria contact: Walid Dabbous and Damien Saucez
- Website: CONVERGE
- Summary: 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 Research Infrastructures (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 recognized 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.

- DIANA project-team's role in the project: DIANA leads Task 2.4, focusing on the design and implementation of a Vision Radio Simulator, a key component of the Digital Twin for the CONVERGE experimental chamber.
- Budget allocated to the DIANA project-team: 431 k€.

**SLICES - PP**

- Title: Scientific Large-scale Infrastructure for Computing/Communication Experimental Studies - Preparatory Phase
- Duration: 40 months (1/9/2022 to 31/12/25)
- Coordinator: INRIA
- Partners: 25 partners with a large intersection with SLICES-SC.
- DIANA project-team contact: Damien Saucez
- Website: SLICES-PP
- Summary: The digital infrastructures research community faces challenges in designing the Next Generation Internet, a complex ecosystem integrating Internet of Things (IoT), 5/6G, and cloud-to-edge computing, alongside data management and intelligence. Addressing the need for experimental research, SLICES-RI, part of the 2021 ESFRI roadmap, aims to build a large-scale infrastructure to support experimentation in distributed computing, networking, and digital technologies. Building on SLICES-DS and SLICES-SC, the SLICES-PP project focuses on validating requirements, defining governance, legal, and financial frameworks, and finalizing the technical architecture for implementation. It seeks to secure commitments from member states and stakeholders, positioning SLICES as a key tool for advancing European research, industrial innovation, and societal impact.
- DIANA project-team's role in the project: we contribute to the definition of the long-term architecture of the SLICES-RI.
- Budget allocated to the DIANA project-team: this project budget was kept in a common pool at the national level.

### 10.2.2 H2020 projects

**SLICES - SC**

- Title: Scientific Large-scale Infrastructure for Computing/Communication Experimental Studies – Starting Community
- Duration: 42 months (1/3/2021 to 31/8/2024)
- Coordinator: Sorbonne University
- Partners: 14 european partners including Sorbonne University (France), TUM (Germany), UTH (Greece), UOulu (Finland), Eurecom (France).
- Inria contact: Walid Dabbous

- Website: SLICES-SC
- Summary: The rapid pace of digital transformation demands advanced computational power and connectivity, driving the need for Research Infrastructures (RIs) tailored to digital sciences. Unlike commercial setups, these RIs offer full control over experiments, repeatability across infrastructures, and validated, replicable results. SLICES RI addresses these needs by enabling high-quality experimentation in areas like 5G/6G, Network Function Virtualization (NFV), IoT, and Cloud Computing at an Internet scale. The SLICES-SC project aims to build a vibrant research community, strengthen ties with industry, and improve research reproducibility and accessibility. Activities focus on providing transnational and virtual access, fostering interdisciplinary collaboration, and advancing experimentation tools.
- DIANA project-team's role in the project: Leading Task 6.4 on event organization within the dissemination work package, alongside significant contributions to the development of the SLICES post-5G Blueprint.
- Budget allocated to the DIANA project-team: 257 k€.

## 10.3 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 NF-MUST, NF-NAI and NF-FPNG.

### 10.3.1 NF-MUST

- Title: End-to-end multi domain services management architecture of the networks of the future
- Coordinator : Djamal Zeghlache (IMT)
- Inria teams participanting to the project : COATI, DIANA, ERMINE
- Summary : The 5G and 6G end-to-end Multi-Domain Services Management Architecture (NF-MUST) project 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", that has started in October 2024.

#### 10.3.2 NF-NAI

- Title: Network and infrastructure architectures and network-cloud-sensing convergence
- Coordinator : Gérard Memmi (IMT)
- Inria teams participanting to the project : AGORA, DIANA, RESIST, TRiBE.
- Summary: The primary challenge of the NF-NAI project lies in the efficient, secure, and cost-effective design, development, planning, and operation of networks and integrated network-cloud-sensing systems. These systems must seamlessly collaborate with diverse sectors of activity while accommodating the broad spectrum of existing applications, each with varying resource and performance demands. Furthermore, they must exhibit the flexibility and agility required to dynamically adapt to evolving future requirements. The NF-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 that haves started in 2024. The first one on "Monitoring plane for mobile cellular networks" and the second on "Experimental evaluation of sliced cellular networks".

#### 10.3.3 NF-FPNG

- Title: French network of test platforms for new-generation mobile communications
- Coordinator: Raymond Knopp, Eurecom
- Inria teams participanting to the project : DIANA, Maracas.
- Summary: The targeted NF-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. NF-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.

### 10.4 Public policy support

The DIANA project-team has been actively engaged in experimental research on next-generation networks for over a decade. Our strong involvement in three PEPR projects — one of which focuses on the French component of the SLICES project — and in SLICES-RI aligns closely with the government's acceleration programs. Our objective is to contribute to preserving telecom sovereignty and to foster advanced technological expertise in networking within France.

# 11 Dissemination

## 11.1 Promoting scientific activities

Chadi Barakat is on the editorial board of the Computer Networks journal. He is/was on the Technical Program Committee for the ACM Internet Measurement Conference (IMC 2024 and 2025), the Mediterranean Communication and Computer Networking Conference (MedComNet 2021, 2022, 2023 and 2024), the International Teletraffic Congress (ITC 36) in 2024. He is currently in charge of international affairs and member of the Comité de Suivi Doctoral (CSD) 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) in the Université Côte d'Azur. He is also member of the scientific committee of the DS4H Graduate school and member of the Ubinet International Master program steering committee. In 2024, he attended the Dagstuhl seminar on Research Infrastructures and Tools for Collaborative Networked Systems Research.

Thierry Turletti is on the editorial board of the Wireless Networks journal published by Springer. He is/was also on the Technical Program Committee for the IEEE Conference on Communications (ICC 2024,2023,2021), Workshop on ns-3 (WNS3 2024-2021), Workshop on Advances in Environmental Sensing Systems for Smart Cities (EnvSys 2024,2023), IEEE/IFIP Network Operations and Management Symposium (NOMS 2024-2022). He was a member of the Comité de Suivi Doctoral (CSD) (2021-2024) and is a member of the Comité de Centre at Inria centre at Université Côte d'Azur since 2024.

Thierry Parmentelat is the principal Engineer in charge of the R2lab testbed. Since 2019 he is involved in the reformation of the Computer Science course at MinesParis-PSL, where he teaches programming. Together with Arnaud Legout, Thierry Parmentelat is a co-author of the MOOC "Python : des fondamentaux aux concepts avancés du langage" that has been running on FUN-MOOC for more than ten years now, and has attracted more than 100,000 users over time.

Damien Saucez is the referent for science popularization at the Centre Inria d'Université Côte d'Azur. His role mostly consists in promoting and organizing science popularization activities within Inria but also outside with schools and general public. He is deeply involved in reproducible research with the ACM where he co-defined Artifacts Evaluation Committees (AEC) for the ACM Special Interest Group on Data Communication, he frequently co-chairs ACM AECs and be port of the volunteers to assess reproducibility for the ACM. To cite only the most recent ones, he co-chaired ACM SIGCOMM'23 AEC, the ACM IMC 2024 and AMC IMC 2025 Reproducibility Track and was regular reproducibility reviewer for the ACM CoNEXT 2023. Damien Saucez has co-organized the IFIP Networking 2024 Hackathon and the TNC2024 Integrated Support of Large Scale Research Instruments BoF.

Arnaud Legout is local correspondent of the Inria ethical committee and member of the Université Côte d'Azur ethical committee (CER) since January 2024. From 2020 to 2023, he was member of the scientific council of the Regalia project for the regulation of AI.

### 11.1.1 Scientific events: organisation

**General chair, scientific chair**

- Damien Saucez frequently co-chairs ACM AECs and be port of the volunteers to assess reproducibility for the ACM. To cite only the most recent ones, he co-chaired:
  - ACM SIGCOMM'23 AEC
  - ACM IMC 2024
  - AMC IMC 2025 Reproducibility Track

**Member of the organizing committees**

- Damien Saucez has co-organized
  - the IFIP Networking 2024 Hackathon
  - the TNC2024 Integrated Support of Large Scale Research Instruments BoF.

#### 11.1.2 Scientific events: selection

**Member of the conference program committees**

- Chadi Barakat is/was a member of the Technical Program Committee for:
  - The ACM Internet Measurement Conference (IMC 2024 and 2025)
  - The Mediterranean Communication and Computer Networking Conference (MedComNet 2024)
  - The International Teletraffic Congress (ITC 36) in 2024
- Thierry Turletti is/was on the Technical Program Committee for
  - The IEEE Conference on Communications (ICC 2024)
  - The workshop on ns-3 (WNS3 2024)
  - The workshop on Advances in Environmental Sensing Systems for Smart Cities (EnvSys 2024),
  - The IEEE/IFIP Network Operations and Management Symposium (NOMS 2024).

**Reviewer**

- Damien Saucez
  - Regular reproducibility reviewer for the ACM CoNEXT 2023.

#### 11.1.3 Journal

**Member of the editorial boards**

- Chadi Barakat
  - Member of the editorial board of the Computer Networks journal.
- Thierry Turletti
  - Member of the editorial board of the Wireless Networks journal published by Springer

#### 11.1.4 Scientific expertise

- Thierry Parmentelat
  - is the principal Engineer in charge of the R2lab testbed.
- Damien Saucez
  - is involved in reproducible research with the ACM where he co-defined Artifacts Evaluation Committees (AEC) for the ACM Special Interest Group on Data Communication.

#### 11.1.5 Research administration

- Chadi Barakat is currently
  - In charge of international affairs and member of the Comité de Suivi Doctoral (CSD) at Inria centre at Université Côte d'Azur
  - 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) in the Université Côte d'Azur.
  - Member of the scientific committee of the DS4H Graduate school.

  - Member of the Ubinet International Master program steering committee.

- Thierry Turletti is
  - Member of the Comité de Suivi Doctoral (CSD) (2021-2024)
  - Member of the Comité de Centre at Inria centre at Université Côte d'Azur (since 2024)

- Damien Saucez is
  - Referent for science popularization at the Centre Inria d'Université Côte d'Azur. His role mostly consists in promoting and organizing science popularization activities within Inria but also outside with schools and general public.

- Arnaud Legout is
  - Local correspondent of the Inria ethical committee,
  - Member of the Université Côte d'Azur ethical committee (CER) since January 2024.

## 11.2 Teaching - Supervision - Juries

### 11.2.1 Teaching

- Master2 Ubinet: Chadi Barakat and Walid Dabbous, Evolving Internet, 21 hours.
- Master2 Ubinet: Arnaud Legout, From BitTorrent to Privacy, 15 hours.
- Master2 Estel - Electronics and Telecommunications Systems: Chadi Barakat, Voice over IP, 6 hours.
- Master1 Computer Science: Chadi Barakat, Computer Networks, 12 hours.
- Master1 Computer Science: Chadi Barakat, Advanced Computer Networks, 12 hours.
- MinesParis-PSL: Thierry Parmentelat has been heavily involved in the reformation of the Computer Science program, that he teaches to the first year students of "Cycle des ingénieurs civils" (Python, git, Web, Data Science).
- Eurecom: Arnaud Legout, AWARE (Awarness-Raising to research), last year students (equivalent to M2), 5 hours
- Eurecom: Arnaud Legout, ComEng (Communication for engineers), 1st year students (equivalent L3), 21 hours
- MOOCs: Arnaud Legout and Thierry Parmentelat are co-authors of the MOOC : "Python 3 : des fondamentaux aux concepts avancés du langage" that lasts 9 weeks on FUN, funded by Université Côte d'Azur. This MOOC has been running since 2014; it was innovative in its form at the time, since it leveraged Jupyter notebooks as a medium for complementing videos, which provides for a hands-on experience and self-correcting exercises. More than 100k persons have subscribed over time, out of which about 10k have received a success badge.
- SLICES Academy is a platform supporting the community by fostering knowledge and engagement of users of testbed facilities with future Internet technologies, including networking, cloud computing, wireless connectivity, and AI/ML. In addition to his involvement in defining the SLICES-RI post-5G blueprint, Damien Saucez delivered two online classes as part of the SLICES Academy: the "SLICES Blueprint" class teaches step by step how to deploy the Post-5G blueprint and the "Kubernetes Clusters for Operators" classes explains how to deploy a Kubernetes cluster dedicated to telecom workload.

### 11.2.2 Supervision

**PhD students**

- PhD defended: Bernard Tamba Sandouno worked on a "Geolocation assessment model of mobile network performance". His PhD was co-supervised by Chadi Barakat, Thierry Turletti and Walid Dabbous from the DIANA team, and by Yamen Alsaba from YDATA. His thesis was funded by a CIFRE grant in collaboration with YDATA. The PhD was defended on July 2024.
- PhD in progress: Yassir Amami started his PhD on "Monitoring plane for mobile cellular networks" in October 2024. His PhD is funded by the PEPR project NF-NAI.
- PhD in progress: Mohammad Bagher Tavassoli started his PhD on "Experimental performance evaluation of sliced cellular networks" in June 2024. His PhD is funded by the PEPR project NF-NAI.
- PhD in progress: Stefano Lioce started his PhD on "RIS-aided Communication" in February 2024. His research is supported by the EU Horizon CONVERGE project and is conducted under a co-tutelle agreement with Politecnico di Bari.
- PhD in progress: Jamil Abou Ltaif began his PhD on "QoE-aware optimization of energy efficiency in mobile networks" in October 2024. His research is conducted in collaboration with researchers from the COATI project team and is supported by funding from the PEPR NF-MUST project.

**Master students**

- Yassir Amami
  - From March until August 2024
  - Ubinet Master, Université Côte d'Azur
  - Subject: Monitoring future cellular networks: interpreting radio interface measurements in terms of user experience
  - Supervisor: Chadi Barakt and Thierry Turletti
- Mattia Ciaccia
  - From March until August 2024
  - Ubinet Master, Université Côte d'Azur
  - Subject: Towards High Resolution LIDAR Data over 5G
  - Supervisor: Damien Saucez and Walid Dabbous
- Mohamed El Khatib
  - From March until August 2024
  - Ubinet Master, Université Côte d'Azur
  - Subject: AI-Assisted Detection of Bitcoin Burn Addresses
  - Supervisor: Arnaud Legout
- Khalid Hachem
  - From March until August 2024
  - Ubinet Master, Université Côte d'Azur
  - Subject: Experimental evaluation of Sliced cellular Networks
  - Supervisor: Chadi Barakt, Thierry Turletti and Walid Dabbous
- Maryam Tamlalti
  - From April until August 2024

- Ubinet Master, Université Côte d'Azur
- Subject: Implementing a 5G network: leveraging CI/CD and automation strategies
- Supervisor: Damien Saucez and Walid Dabbous

- Saadeddine Tazili
  - From March until August 2024
  - Ubinet Master, Université Côte d'Azur
  - Subject: Experimenting and Modeling Energy Consumption & Quality of Experience in Next-Gen Cellular Networks
  - Supervisor: Chadi Barakat and Thierry Turletti

#### 11.2.3 Juries

- Chadi Barakat served as president and examiner of Olga Chuchuk PhD thesis "Data access optimisation at CERN and in the Worldwide LHC Computing Grid (WLCG)", defended in February 2024 at CERN, Switzerland.
- Walid Dabbous served as president of the HDR Defense Committee (Habilitation à Diriger des Recherches) for Christelle Caouillet at Université Côte d'Azur, where she presented her research titled "Modeling and Optimizing Wireless Networks: FANET and LoRaWAN" in March 2024.
- Walid Dabbous served as president of the PhD Defense Committee for Angelo Rodio at Université Côte d'Azur, where he presented his research titled "Client Heterogeneity in Federated Learning Systems" in July 2024.
- Walid Dabbous served as member of the second year PhD monitoring committee (CSI) for Anderson Lourenço de Araujo at Université Côte d'Azur in September 2024. The thesis is co-supervised by Luc Deneire and Guillaume Urvoy-Keller.
- Arnaud Legout served as member of the first year PhD monitoring committee (CSI) for Francesco Diana at Université Côte d'Azur in September 2024. The thesis is co-supervised by Giovanni Neglia and Chuan Xu.
- Thierry Turletti served as reviewer of Abderaouf Khichane PhD thesis entitled "Diagnostic of performance by data interpretation and corrective actions for 5G cloud-native network functions" defended on March 2024 at Paris Saclay University.

### 11.3 Popularization

#### 11.3.1 Specific official responsibilities in science outreach structures

**Participants:** Damien Saucez, Walid Dabbous.

**Terra Numerica** is a large-scale unifying project aimed at promoting digital science culture. It is led by CNRS, Inria and the Université Côte d'Azur and brings together a wide range of partners, including the French National Education system (notably the Regional Academic Directorate for Digital Education). Terra Numerica has developed an original, engaging and unique framework for dissemination, collaboration, and interaction among digital science stakeholders. This includes an iconic hub for promoting digital science culture, Terra Numerica@Sophia, a network of Partner Spaces throughout the Sud region, as well as outreach initiatives and online activities. The original workshops held in these spaces offer a way to engage science in a fun and enjoyable manner. DIANA members are actively involved in science popularization through Terra Numerica, frequently organizing activities for school classes visiting the center. In addition, project team members play a key role in the CHICHE program, visiting high schools to inspire and encourage students to pursue higher education in scientific fields.

### 11.3.2 Others science outreach relevant activities

Our project-team is actively involved in initiatives targeting both schools and the general public, with a particular focus on fostering gender diversity in scientific research:

- School Outreach through the Chiche Program: Researchers visit high schools to encourage students of all genders and backgrounds to pursue scientific studies.
- 9th Grade Student Visits: The team hosts 9th graders, introducing them to their research activities to spark scientific interest among a wide demographic.

# 12 Scientific production

## 12.1 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. URL: https://hal.inria.fr/hal-03230168.

[2] Y. Boussad, X. L. Chen, A. Legout, A. Chaintreau and W. Dabbous. 'Longitudinal study of exposure to radio frequencies at population scale'. In: *Environment International* 162 (24th Mar. 2022). DOI: 10.1016/j.envint.2022.107144. URL: https://inria.hal.science/hal-03618634.

[3] M. Diarra, W. Dabbous, A. Ismail, B. Tetu and T. Turletti. 'RAPID: a RAN-aware Performance Enhancing Proxy for High Throughput Low Delay Flows in MEC Networks'. In: *Computer Networks* 218.9 (9th Dec. 2022), p. 109357. DOI: 10.1016/j.comnet.2022.109357. URL: https://inria.hal.science/hal-03905784.

[4] H. Elbouanani, C. Barakat, W. Dabbous and T. Turletti. 'Fidelity-aware Large-scale Distributed Network Emulation'. In: *Computer Networks* (28th May 2024). DOI: 10.1016/j.comnet.2024.110531. URL: https://inria.hal.science/hal-04591699.

[5] S. Fdida, N. Makris, T. Korakis, R. Bruno, A. Passarella, P. Andreou, B. Belter, C. Crettaz, W. Dabbous, Y. Demchenko and R. Knopp. 'SLICES, a scientific instrument for the networking community'. In: *Computer Communications* 193 (Sept. 2022), pp. 189–203. DOI: 10.1016/j.comcom.2022.07.019. URL: https://hal.science/hal-03941155 (cit. on p. 7).

[6] D. Saucez, S. Gallenmüller, R. Knopp, N. Makris and S. Fdida. 'Blueprint-based reproducible research with the SLICES Research Infrastructure'. In: IEEE INFOCOM 2024 - IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS). Vancouver, BC, Canada: IEEE, 13th Aug. 2024, pp. 01–02. DOI: 10.1109/INFOCOMWKSHPS61880.2024.10620849. URL: https://inria.hal.science/hal-04755912.

[7] B. Tamba Sandouno, Y. Alsaba, C. Barakat, W. Dabbous and T. Turletti. '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. URL: https://inria.hal.science/hal-04157758 (cit. on p. 9).

[8] T. Yuan, W. Borba da Rocha Neto, C. E. Rothenberg, K. Obraczka, C. Barakat and T. Turletti. 'Machine Learning for Next-Generation Intelligent Transportation Systems: A Survey'. In: *Transactions on emerging telecommunications technologies* 33.4 (Apr. 2022). DOI: 10.1002/ett.4427. URL: https://inria.hal.science/hal-02284820 (cit. on p. 10).

## 12.2 Publications of the year

**International journals**

[9] H. Elbouanani, C. Barakat, W. Dabbous and T. Turletti. 'Fidelity-aware Large-scale Distributed Network Emulation'. In: *Computer Networks* (28th May 2024). DOI: 10.1016/j.comnet.2024.110531. URL: https://inria.hal.science/hal-04591699 (cit. on p. 9).

[10] H. Elbouanani, C. Barakat, W. Dabbous and T. Turletti. 'Troubleshooting Distributed Network Emulation'. In: *Annals of Telecommunications - annales des télécommunications* 79.April (19th Feb. 2024), pp. 227–239. DOI: 10.1007/s12243-024-01010-y. URL: https://inria.hal.science/hal-04373896 (cit. on p. 9).

[11] A. Kaul, K. Obraczka, R. dos Reis Fontes and T. Turletti. 'D4: Dynamic, Decentralized, Distributed, Delegation-Based Network Control and Its Applications to Autonomous Vehicles'. In: *ACM Journal on Autonomous Transportation Systems* (2024). URL: https://inria.hal.science/hal-04408891. In press (cit. on p. 10).

**International peer-reviewed conferences**

[12] N. Kirimi, C. Barakat and Y. Hadjadj-Aoul. 'Passive network monitoring and troubleshooting from within the browser: a data-driven approach'. In: IWCMC 2024 - 20th International Wireless Communications & Mobile Computing Conference. Ayia Napa, Cyprus, 2024, pp. 1–6. URL: https://inria.hal.science/hal-04564562 (cit. on p. 9).

[13] 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 (cit. on p. 10).

[14] D. Saucez, S. Gallenmüller, R. Knopp, N. Makris and S. Fdida. 'Blueprint-based reproducible research with the SLICES Research Infrastructure'. In: IEEE INFOCOM 2024 - IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS). Vancouver, BC, Canada: IEEE, 13th Aug. 2024, pp. 01–02. DOI: 10.1109/INFOCOMWKSHPS61880.2024.10620849. URL: https://inria.hal.science/hal-04755912 (cit. on pp. 8, 12).

[15] B. Tamba Sandouno, C. Barakat, T. Turletti and W. Dabbous. 'Optimizing Ray Tracing Techniques for Generating Large-Scale 3D Radio Frequency Maps'. In: WoWMoM 2024 - 25th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks. Perth, Australia, 4th June 2024. URL: https://inria.hal.science/hal-04546462 (cit. on p. 9).

**Doctoral dissertations and habilitation theses**

[16] B. T. Sandouno. 'Enhancing outdoor radio frequency mapping with Ray Tracing techniques'. Université Côte d'Azur, 13th June 2024. URL: https://theses.hal.science/tel-04767356 (cit. on p. 9).

**Reports & preprints**

[17] S. Lioce. *Technical report of RIS-aided communication*. DIANA, Centre INRIA d'Université Côte d'Azur, Sept. 2024. URL: https://hal.science/hal-04692924 (cit. on p. 11).

[18] D. Saucez and L. Iannone. *Locator/ID Separation Protocol Delegated Database Tree (LISP-DDT)*. IETF, Nov. 2024. URL: https://inria.hal.science/hal-04907679 (cit. on p. 12).

[19] N. Schnepf, R. Badonnel, D. Saucez, J. Sbara and S. Schmid. *Towards Vulnerability and Congestion Aware Software Update Synthesis for Softwarized Networks*. 22nd Jan. 2025. URL: https://inria.hal.science/hal-04906917 (cit. on p. 11).

**Other scientific publications**

[20] D. Saucez. *A blueprint for the new research instrument*. 29th Jan. 2024. URL: https://inria.hal.science/hal-04756126 (cit. on p. 12).

[21] D. Saucez. *How the SLICES research instrument leverages OAI to reach reproducible research*. 12th Sept. 2024. URL: https://inria.hal.science/hal-04756070 (cit. on p. 12).

[22] D. Saucez and N. Makris. *Thought experiments, data and reproducibility for networking and FutureG research: Hackathon*. 3rd June 2024. URL: https://inria.hal.science/hal-04755954 (cit. on p. 12).

[23] D. Saucez, R. Trasarti and B. Belter. *Integrated Support of Large Scale Research Instruments*. 12th June 2024. URL: https://inria.hal.science/hal-04756028 (cit. on p. 12).

## 12.3 Cited publications

[24] T. Yuan, W. D. Rocha Neto, C. E. Rothenberg, K. Obraczka, C. Barakat and T. Turletti. 'Dynamic Controller Assignment in Software Defined Internet of Vehicles through Multi-Agent Deep Reinforcement Learning'. In: *IEEE Transactions on Network and Service Management* 18.1 (Mar. 2021), p. 12. DOI: 10.1109/TNSM.2020.3047765. URL: https://inria.hal.science/hal-03000911 (cit. on p. 10).

[25] T. Yuan, C. E. Rothenberg, K. Obraczka, C. Barakat and T. Turletti. 'Harnessing UAVs for Fair 5G Bandwidth Allocation in Vehicular Communication via Deep Reinforcement Learning'. In: *IEEE Transactions on Network and Service Management* (2021). DOI: 10.1109/TNSM.2021.3122505. URL: https://inria.hal.science/hal-03001383 (cit. on p. 10).