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Innovation and excellence in massive-scale communications and information processing

INCOMING (Project No. 856967)

D2.3: Novel massive IoT solutions, SDR implementation and 5G-IT-hub showcasing[1]

Abstract: This document presents a report on the WP2 research and development activities including the description of novel algorithms and methodologies developed within Tasks 2.1 and 2.2 and their implementation in real-world prototypes in the domain of massive Internet of Things.

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List of Abbreviations

AAU	Aalborg University
CHALMERS	Chalmers University of Technology
DL	Deep Learning
DLR	German Aerospace Centre
EU	European Union
EPC	Evolved Packet Core
FTN	Faculty of Technical Sciences, University of Novi Sad
ICT	Information and Communication Technologies
IoT	Internet of Things
MCU	Micro-Controller Unit
ML	Machine Learning
NFV	Network Function Virtualization
OAI	OpenAirInterface
RF	Radio Frequency
SDR	Software Defined Radio
SDN	Software Defined Networks
UAV	Unmanned Aerial Vehicles
UNS	University of Novi Sad
VLC	Visible Light Communications

Executive Summary

Centre for intelligent communications, networking and information processing (ICONIC) at the Faculty of Technical Sciences, University of Novi Sad, aimed to significantly upgrade its capacities for fundamental theoretical work and to create testbed and experimentation capacities in the domain of massive IoT systems, providing a support for the proof-of-concept demonstrations and innovative solutions. The report focuses on significant expertise developed at ICONIC centre in designing, analysing, implementing and demonstrating low-power wide area networking (LP WAN) IoT solutions both in licensed and unlicensed frequency bands. In a licensed band, 3GPP mobile cellular network extensions to support massive IoT (e.g., NB-IoT and LTE-M) are the focus of the ICONIC centre research and development. In an unlicensed band, outdoor wide-area solutions such as LoRaWAN, and indoor solutions based on Optical Wireless Communication (OWC) technologies are important aspect of the ICONIC centre work. This report provides an in-depth explanation of the main outcomes of the ICONIC centre research and development in the domain of massive IoT during the INCOMING project, and explains its prospects beyond the project lifetime.

1 Introduction

The focus of WP2 is to coordinate research and development activities and knowledge transfer from EU partners to ICONIC researchers in the domain of massive IoT technologies. Through well balanced blend of staff exchanges, summer schools and expert training, this WP boosted the research level of ICONIC researchers, while contributing to their prototyping skills using hardware-based platforms and flexible software defined radios (SDR) modules.

In this report, we describe how the INCOMING project enhanced ICONIC centre development and innovation capacity focusing on high quality analytical work in the domain of system modeling and analysis, and fast prototyping skills of ICONIC researchers on hardware-based SDR platforms. We first review how the work in WP2 has been organised in the form of focused development-oriented mini-projects aligned with staff exchanges. Aggregating contributions from mini-projects we describe in this report the final outcomes of WP2.

Note that, due to COVID-19 situation that affected the INCOMING project already during the M3 of the project realization, in the period between 2020-2022, the project activities on WP2 tasks have been moved to online mode. This constraint has significantly affected the part of the project development that deals with prototyping activities as they particularly benefit from face-to-face meetings and day-to-day interaction.

We start this report by presenting the list of research-oriented and development-oriented mini-projects that are identified as promising before the mid-term review meeting M15 of the project (March 2021) and extend or alter this list based on the developments that took place between M15 and M40 of the project.

2 Evolution of Research and Development Mini Projects

WP2 research and development activities are coordinated by AAU as a WP leader, with a strong support from DLR and CHALMERS. By M12 of the project, 7 research mini-projects are set up between ICONIC researchers and EU partners in the domain of massive IoT in radio-frequency (RF) and visible light communications (VLC). The list of research mini-projects, including the staff members involved, starting month and the status of the project after the first reporting period (RP1), is presented in the table below.

Table 1. List of research mini-projects initiated in WP2 during RP1

MP No.	Mini-project title	Start	Team	Status (M15)
MP-R-2.1	Relay-aided Slotted ALOHA for Optical Wireless Communications	M3	Milica Petkovic (FTN), Dejan Vukobratovic (FTN) Andrea Munari (DLR) Federico Clazzer (DLR)	Conference paper published (CNSDSP 2020). Ongoing work towards journal paper.
MP-R-2.2	Slotted ALOHA for Indoor Optical Wireless Communications with Capture	M6	Milica Petkovic (FTN) Tijana Devaja (FTN) Dejan Vukobratovic (FTN) Cedomir Stefanovic (AAU)	Journal paper is prepared in the draft form.
MP-R-2.3	Random Access for Energy Harvesting IoT devices	M4	Jelena Bjelica (FTN) Milica Petkovic (FTN) Dragana Bajovic (FTN) Dejan Vukobratovic (FTN) Gianluigi Liva (DLR)	Initial results obtained. Work continues towards journal paper.
MP-R-2.4	Massive Internet of Things: Fundamentals and Applications	M6	Gianluigi Liva (DLR) Dejan Vukobratovic (FTN) Cedomir Stefanovic (AAU) Alexandre Graell i Amat (CHALMERS)	Overview paper for BalkanCom 2021 INCOMING special session (conference postponed due to COVID-19)
MP-R-2.5	Generalized Component Code Design using short nonlinear component codes	M9	Aleksandar Minja (FTN) Vojin Senk (FTN) Balasz Matus (DLR) Gianluigi Liva (DLR)	Work in progress. Initial designs in the process of evaluation.
MP-R-2.6	Mixed IoT RF and FSO backhaul communication system design	M9	Milica Petkovic (FTN) Milan Narandzic (FTN) Dejan Vukobratovic (FTN)	Initial work done by FTN ICONIC team. DLR FSO team to be involved in the next stage.
MP-R-2.7	Properties of Run-Length Limited Sequences for Visible Light Communications	M9	Mladen Kovacevic (FTN) Dejan Vukobratovic (FTN)	Initial work done by FTN ICONIC team. CHALMERS coding team to be involved in the next stage.

Note that one of the research mini-projects (MP-R-2.1) resulted in the first joint conference publication between ICONIC and DLR researchers achieving the milestone MS5 (first joint conference paper accepted for publication).

In addition, by M12 of the project, 5 development mini-projects are set up with active participation of ICONIC researchers and guidance provided by EU partners in the domain of massive IoT in RF and VLC domain. The list of development mini-projects, including the staff members involved, starting month and the current stage of the project, is presented in the table below.

Table 2. List of development mini-projects initiated in WP2 during RP1

MP No.	Mini-project title	Start	Team	Status (M15)
MP-D-2.1	3GPP NB-IoT testbed for NB-IoT module energy consumption modelling and evaluation	M3	Milan Lukic (FTN) Srdjan Sobot (FTN) Ivan Mezei (FTN) Dejan Vukobratovic (FTN)	Conference paper published (IEEE Smart IoT 2020). Work towards journal paper in progress.
MP-D-2.2	3GPP NB-IoT testbed deployment for indoor illumination modelling and positioning	M6	Milan Lukic (FTN) Srdjan Sobot (FTN) Ivan Mezei (FTN) Milica Petkovic (FTN) Dejan Vukobratovic (FTN)	Testbed comprising 20 NB-IoT devices deployed and initial data set collected.
MP-D-2.3	UAV-assisted NB-IoT/LoRa network for deep rural coverage	M9	Milan Lukic (FTN) Srdjan Sobot (FTN) Dejan Vukobratovic (FTN)	Initial version of the solution successfully demonstrated.
MP-D-2.4	Image/video capturing and streaming from UAVs via low-cost 3GPP NB-IoT/LTE-M devices	M9	Vladimir Nikic (FTN) Dusan Bortnik (FTN) Milan Lukic (FTN) Ivan Mezei (FTN) Dejan Vukobratovic (FTN)	Initial version of the solution successfully demonstrated.
MP-D-2.5	Integrated end-to-end 4G/5G testbed environment using OAI eNB and OpenStack virtualized EPC	M12	Goran Martic (FTN) Srdjan Sobot (FTN) Nikola Gavric (FTN) Nemanja Krajcinovic (FTN) Zivko Bojovic (FTN) Dejan Vukobratovic (FTN)	Work in progress.

Based on the above, and after careful examination of future core research topics of ICONIC centre driven by reviewer comments during the mid-term review meeting, the list of research and development mini projects has been refined and aggregated into a new list of four tracks of research and development in massive IoT domain. The list is developed taking into account the objectives listed below:

- **Fundamental research results:** Where applicable, we start review of each research and development topic by presenting theoretical results developed during the project that have been published in renowned (IEEE) conference and journal venues.
- **IoT testbed identification:** Identify and integrate a selected set of IoT testbeds that would enable ICONIC researchers to gain experimental and development skills and quickly turn their ideas into prototypes.
- **Massive IoT solutions identification:** Within each of the identified wireless testbeds, identify and develop specific demo use cases that will demonstrate the testbed capabilities and direct the development towards innovative solutions.
- **Testbed/Use case exploitation:** Demonstrate the selected solutions implemented within wireless testbed environment to: 1) showcase the demos at 5G-IT-Hub events, 2) produce relevant data sets during and beyond the project lifetime, 3) publish demo papers at relevant conferences and journals, 4) use testbed demos as an asset for EU and national funding project applications.

The following four research and development tracks are proposed for evolution during the remaining period of the project: 1) Integrated end-to-end 4G/5G communication platform, 2) Massive Cellular IoT: fundamentals and testbed development, 3) UAV-based Cellular IoT: fundamentals and testbed development, and 4) Indoor OWC IoT system: fundamentals and testbed development. Each track is described by first presenting in detail the fundamentals and the theoretical advances developed during the project, the testbed that underlies the solution, which is identified as a fundamental infrastructure for future research and development in the domain of wireless communications and massive IoT. Current state of the testbed is presented along with the plans for the testbed evolution during and beyond the project lifetime. The report identifies the massive IoT solutions that are developed or a in the process of development on top of a given testbed infrastructure in the form of specific use cases and their demonstrations. Finally, we outline the outreach and dissemination activities related to each solution.

To summarize, for each of the four massive IoT solution research track developed during the INCOMING project, we describe: 1) the fundamental research work done, 2) the testbed in which the solution will be integrated, and 3) the solution itself through specific demo use case and comment on how such use case was exploited during the project and after its lifetime.

3 Integrated End-to-End 5G Communication Platform

As any asipirative research group that works in the domain of wireless communications, IoT and cellular 5G and beyond technology, ICONIC centre requires testbed infrastructure where future researchers will be trained and educated, and where fast prototyping and testing of the proposed solutions will be tested and evaluated. We start this report by describing current state of the affairs and ongoing efforts done during the INCOMING project to integrate a testbed and experimentation platform that could be used by ICONIC researchers to research and develop novel solutions in the domain of 5G and beyond technologies.
When the project started in 2020, the overall direction on how to build integrated ICONIC wireless experimentation platform has been defined as illustrated in the figure below.

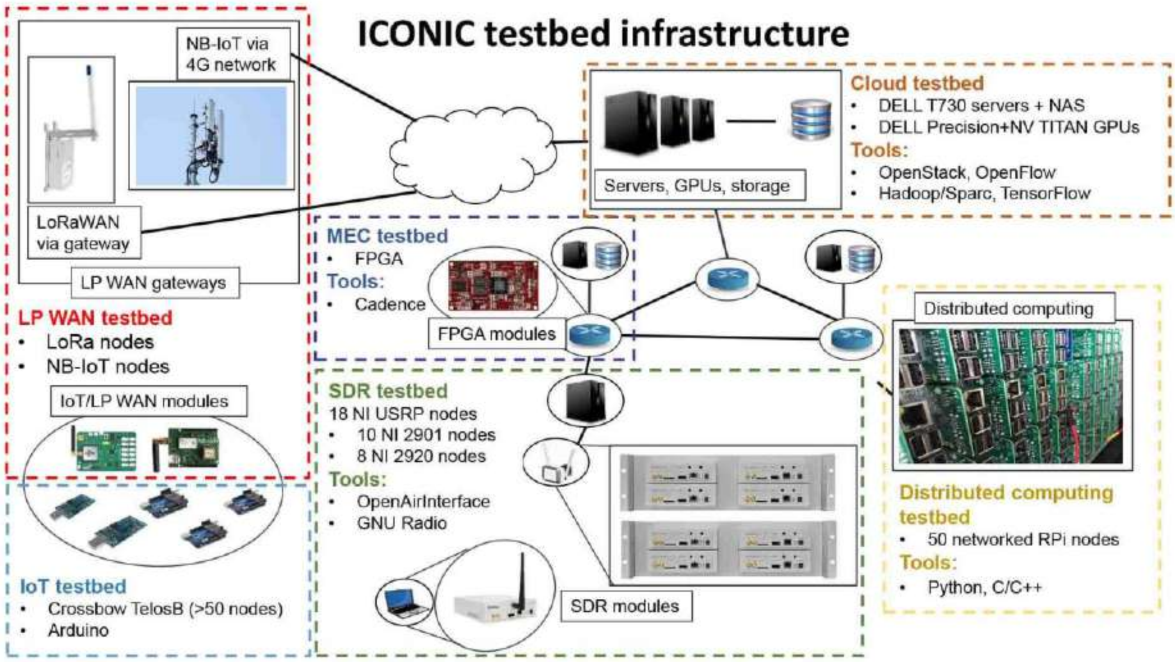

Figure 1. ICONIC 4G/5G-enabled research infrastructure

The proposed testbed evolved over the course of INCOMING project in multiple directions. In the following, we briefly comment on each module within the overall testbed infrastructure.

SDR-based wireless testbed: Our wireless testbed consists of 18 software-defined radio (SDR) USRP modules B210 and N210 which are versatile to cover various wireless communication standards. In combination with MATLAB, GnuRadio, LabView or similar tools, it can be used for design and experimentation with different communication standards and of different PHY processing algorithms. Using open-source frameworks such as OpenAir Interface (OAI) and srsRAN, one can build fully functional 4G or 5G network in the lab. Both tools are continuously evolving according to O-RAN standardization into a set of software-based RAN modules (central, distributed and radio unit) that can be flexibly used and experimented with in the lab. More details on how at ICONIC we use this testbed is presented in Section 4.

Massive IoT testbed: Particular focus of ICONIC is the domain of cellular IoT technologies, i.e., in fundamental terms, how to address in analytical terms the design of such networks, and in practical terms, how to develop large-scale testbed and experiment with the technology in practice. In general, the design of Low-Power Wide Area Networks (LPWAN) assumes balancing the trade-offs between: i) interference, modeled using stochastic geometry, ii) short packet transmission reliability, quantified by the finite block-length information theory, and iii) the random access mechanism. In Section 5, we describe the work done during the INCOMING project on massive IoT in cellular networks, both for the analytical perspective and from the perspective of demonstration and experimentation using the two most popular low-power wide area network (LP WAN) technologies: 3GPP Narrowband IoT (NB-IoT) and LoRa.

UAV communications testbed: UAVs or drones have a huge potential to address various use cases that involve provisioning of communication infrastructure anytime and anywhere for a wide variety of applications. In ICONIC, we are early adopters of drones as a communication infrastructure and during the INCOMING project, we have been experimenting with drones as stand alone 4G/5G networks based on OAI and srsLTE RAN/Core software and using SDR radio units. However, the major use case we consider and build UAV testbed for is related to deep rural IoT connectivity. Collecting or streaming the data from remote and unconnected devices in rural areas in the central use case of the experimentation platform developed at ICONIC that is described in detail in Section 6.

Indoor Optical Wireless Communication (OWC) testbed: The INCOMING project significantly helped the development of OWC-based research at ICONIC. Unlike majority of the research community that consider OWC as high data-rate interface for indoor access to Internet (e.g., through Li-Fi concept), we consider OWC as a low cost low data rate indoor IoT technology. We find it suitable to complement RF-based IoT solutions, especially as more and more IoT devices are connected and we expect to see capacity limits being reached soon at lower RF bands. Section 7 provides details on our fundamental and applied work in the domain of OWC IoT connectivity.

4 Testbed for integrated end-to-end 5G communications

Background: In recent years, academic research in mobile cellular networks becomes increasingly reliant on usage of reconfigurable software-defined radio (SDR) hardware platforms and the corresponding software support that enables fast prototyping, testing and measurements related to emerging 5G and beyond 5G cellular technologies. This has become a reality mainly due to availability of low-cost SDR platforms and open-source software for implementation of complete 4G and 5G radio access network and core network protocols on commodity hardware (high-performance computers and servers). ICONIC centre follows this path and actively participates in education, PhD training, research and development using open software/hardware platforms [1].

Hardware support: For the development of integrated end-to-end 4G/5G testbed, ICONIC possesses all necessary equipment, including:

- 18 National Instruments USRP 2901-2920 (B210/N210) SDR devices
- Intel NUC core-i7 mini PC computers for compact base station (eNB/gNB) deployment
- 3 high-performance servers with network-attached storage (NAS), NVIDIA Titan graphical processing units (GPUs) and large storage capacity

Software support: Regarding the software-based 4G/5G network implementation, ICONIC is focused on OpenAirInterface (OAI) developed by OAI community around EURECOM institute in France (for more information, please check https://gitlab.eurecom.fr/oai/openairinterface5g), and srsLTE software developed by software radio systems in Ireland (https://www.srslte.com/). Both solutions are open-source and available for academic research, and provide software for user equipment (UE software) processing, 4G and 5G base station processing (eNB and gNB software) and 4G and 5G evolved packet core (EPC) network elements. Besides OAI and srsLTE, in ICONIC, we also use open-source LTEBox EPC software provided by Nokia for academic use.

Testbed integration: At the present stage, both OAI and srsLTE 4G networks have been tested and installed in ICONIC lab as illustrated both schematically and as a real-world setup in Figure 1 below. The testbed is operable and it is possible to connect both commercial off-the-shelf (COTS) UE using programmable SIM cards, 4G or 5G evaluation development boards (e.g., we use Quectel RM500 5G NR modules) and fully softwarized UE (e.g., lap top running 4G/5G UE software connected to USRP SDR device). Combination of software modules of different open-source software providers is also feasible, e.g., we could use OAI-based 4G eNB software with Nokia LTEBox 4G EPC software.

Final integrated and virtualized end-to-end 4G/5G testbed (M32): With proliferation of software virtualization technologies, and expansion of software defined networking (SDN) and network function virtualization (NFV), the trend is to introduce such flexibility in testbed setup. In this sense, we are now deploying and experimenting with open source 5G core network software using Docker and Kubernetes. This way, we are able to exploit virtualization principles and integrate existing open source solutions (such as Mosaic 5G) or develop custom-designed virtualization environment, e.g., based on OpenStack. The goal is to deploy, scale, test, perform measurements and extract KPIs across 5G core network elements (AMF, SMF and other NFs) in containter environment and support experimentation with network slicing.

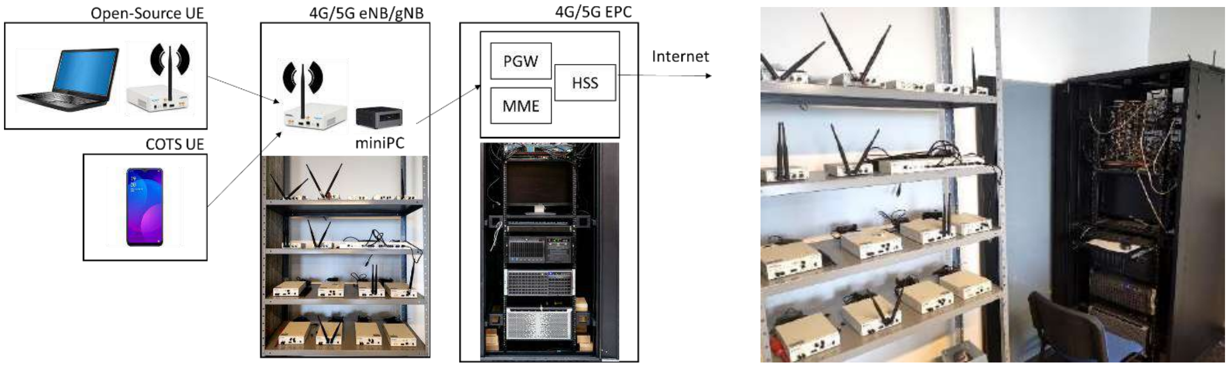

Figure 2. Wireless SDR testbed

Massive IoT solutions for research, demonstration and innovation: The above described 4G/5G experimentation testbed is a necessity for design, deployment and demonstration of various algorithms, applications and services build upon 4G/5G radio interfaces. Experimentation in the lab is critical for development of proof-of-concept demonstrations, for initial measurements and tests, and overall understanding of the technology. Experience with the lab setup described above was instrumental for easier integration of the testbed solutions described below. For this reason, our work on future testbed development and enhancement will continue with the goal of complete integration of several use cases fundamental for future ICONIC research.

- NB-IoT network in the lab: Both OAI and srsLTE open-source solutions for 4G/5G are in the process of development of NB-IoT extension. For srsLTE, only specific channels and procedures are currently available, and we have tested it in the lab. For OAI, NB-IoT solution is completed however with certain issues to be resolved. Our goal is a full end-to-end integration of NB-IoT network in the lab, where our custom-designed NB-IoT devices (see the following subsection) would connect to EPC-based IoT servers. That would provide a platform for end-to-end IoT service design, tests and measurements, including optimization of uplink/downlink configurations, and device energy consumption.
- 4G/5G Core Network Virtualization: At the initial stage, EPC/5GC software was mainly installed as a standard software running on top of a conventional operating system. To allow flexible deployment of core network elements, we developed a testbed where core network functions are virtualised and containerised. Such a flexible core network setup will allow experimentation with service provisioning and quality of service control via network slicing.

Exploitation and outreach directions: The above 4G/5G testbed will serve mainly as an in-lab testing and experimentation platform used as a first phase of development. After specific use case or application is tested in the lab environment, in the next stage, it will be tested via mobile operator network. Software-based testbeds are suitable due to their (re-)configurability and flexibility in selection of the PHY parameters. For example, testing and evaluation of NB-IoT network configurations in the lab would preferably precede experiments in the live network.

5 Massive IoT Communications: Fundametals and Testbeds

Background: With the increasing number of devices used by people, wireless communication technology has become more and more crucial over time. It allows us to easily access information while on the move. Planning for the future of mobile networks has several challenges due to the complexity of managing networks. The growth of the wireless connectivity industry is primarily driven by several factors. Firstly, there is a rising demand for wireless sensor networks, especially in the development of smart infrastructure. Secondly, there has been a significant increase in internet usage worldwide, leading to a higher demand for connectivity. Additionally, the adoption of the Internet of Things (IoT) has been on the rise, contributing to the industry growth. One particular aspect of the IoT is the increased demand for low-power wide-area networks (LP WAN), which are specifically designed for IoT applications. LP WAN technologies offer unique features such as wide-area connectivity for a large number of devices, low energy consumption, and support for low data rate devices. The concept of the IoT extends beyond the traditional internet model based on computers to a more diverse and interconnected network of various devices. According to the GSM Association, it is estimated that by the end of 2018, there were around 22 billion IoT connected devices in use worldwide. Furthermore, it is projected that the number of IoT devices will reach 25.1 billion by the year 2025, indicating the growth and importance of IoT in our lives.

5.1 Fundamentals of Massive IoT in Finite Block-Length Regime

In a wireless network with multiple scattered nodes, there are various obstacles that affect communication, such as wireless propagation effects, network interference, and thermal noise. Our focus is to determine the probability of successfully delivering a data packet from an active IoT device to a base station, considering the presence of concurrent sporadically active IoT devices as potential interferers. Since IoT communications involve sporadic short packet transmissions and the activity of devices is unpredictable so the common approach to address this problem is to use random access (RA) protocols. The system we consider is based on the slotted ALOHA (SA) protocol, where each device has a probability of being active in each time slot. Analyzing packet loss rate and system capacity in ALOHA networks typically involves stochastic geometry. When the locations of transmitters are modeled as a Poisson point process (PPP), different approaches can be used to characterize the interference power. These range from treating the Laplace transform (LT) of interference, to providing characteristic functions and moment generating functions. In the case of Rayleigh fading, the LT of aggregate interference simplifies the analysis and helps in characterizing various system performance metrics. The probability density function (PDF) of interference power can be derived if its LT can be expressed using the Kohlrausch-Williams-Watts (KWW) function, which is directly related to the Laplace domain of the Levy distribution. For the specific case of $\eta=4$ and Rayleigh fading, it can be easily verified that the exact analytical expression of the interference PDF can be obtained. By treating interference as noise and utilizing interference power statistics, our focus is on calculating the average error probability of successfully receiving a data packet at the nearest base station [2]. After deriving this quantity using the standard asymptotic Signal-to-Interference-plus-Noise Ratio (SINR) threshold approach, we further refine the expression by deriving more precise error probability expressions using finite-length information theory results [3], [4]. Our main findings are summarised in a paper that is currently in review for IEEE Wireless Communication Letters [5].

In our analysis, the scenario we consider is a large-scale wireless network that consists of set of base stations (BSs) whose locations form a stationary PPP (Poisson Point Process) with appropriate spatial density. The devices send data to BSs using the SA protocol where the time is divided into equal-length slots. Devices are independently active in each slot, regardless other devices in the network. The goal is to find probability that the device will be successfully decoded at the geographically nearest BS.

Asymptotic analysis assumes that an error event occurs if the SINR γ, is below a predefined threshold γ_{th}. For the suburban environment (path loss error exponent value of η = 4) and the appropriately derived interference probability density function, we present a novel closed-form expression for the asymptotic (threshold-based) error probability using Meier's functions as:

$$P_e = 1 - \frac{1}{2\pi^3} G_{4,4}^{4,4}\left(\frac{t^4 \gamma_{\mathrm{th}}{}^2}{(\lambda_b \pi)^4} \middle| \begin{matrix} 0,\frac{1}{4},\frac{1}{2},\frac{3}{4} \\ 0,\frac{1}{2},\frac{1}{4},\frac{3}{4} \end{matrix}\right).$$

where t=πpλ_uΓ(1+$\frac{1}{2}$)Γ(1−$\frac{1}{2}$), p is the probability that the user is active, and $\lambda_u$is the density of users in the network.

A branch of information theory that analyses the trade off between channel coding rate and error probability under the finite frame length is called finite block-length information theory [4]. The theorem of Shannon–Hartley describes maximum amount of error-free digital data that can be transmitted over a communications channel with a specified bandwidth in the presence of noise. It is developed under the hypothesis of an infinite length frame, and in order to approach Shannon capacity it is necessary to use codes with large block length. The physical-layer design of current systems relies on guidelines provided by information-theory analyses. But to approach capacity, we need to use codes with large block length, which is not realistic in IoT systems and in case of ultra-reliable control systems requiring low latency. Thus we cannot use classic performance metric such as ergodic capacity or outage capacity to benchmark the performance of such systems.

For the case of finite block-length error probability we consider a more realistic model where devices transmit short-length packets encoded using finite-length error correcting code. In our work we managed to tightly approximated the error probability as

$$P_e^{fbl} \approx \frac{t\sqrt{\theta - \mathrm{a}}}{\left(\lambda_b \pi + 2t\sqrt{\theta - \mathrm{a}}\right)} + \left(\frac{1}{4} + \frac{\mu\theta}{2\sqrt{2\pi}}\right)\left[\left(1 + \frac{2t\sqrt{\theta - \mathrm{a}}}{\lambda_b \pi}\right)^{-1} - \left(1 - \frac{2t\sqrt{\theta + \mathrm{a}}}{\lambda_b \pi}\right)^{-1}\right]$$

where $\mu = \sqrt{\frac{n}{2\pi(2^{2R}-1)\log_2^2 e}}$, n is block length and R is code rate, and $a = \sqrt{\frac{\pi}{2\mu^2}}$ for $\theta = 2^R - 1$

In the ongoing work [5], we extended these results to Nakagami fading and standard shadowing distributions and in the future, we will consider various realisation of random access models beyond the conventional but widespread SA protocol.

5.2 Testbed and solutions for massive NB-IoT communications

Background: One of the focal topics of the INCOMING project is massive cellular IoT communications to which WP2 is devoted. The first 3GPP standards that introduced cellular IoT arrived as part of Release 13 (December 2016). Among three cellular IoT standards introduced in R13, the Narrowband IoT (NB-IoT) attracted and still attracts most of the attention. Initial ICONIC experimentation in the domain of NB-IoT started in early 2017. in collaboration with A1 mobile operator in Serbia. Initially based on the first commercially available test devices, ICONIC quickly switched to custom-based NB-IoT devices that provide more flexibility in gathering the data from NB-IoT communication module, including radio channel quality information, full logs of message exchanges between the UE and the eNB, as well as the high-resolution energy consumption data [6]. Two different platforms are designed and fabricated in collaboration with A1 (Figure 3).

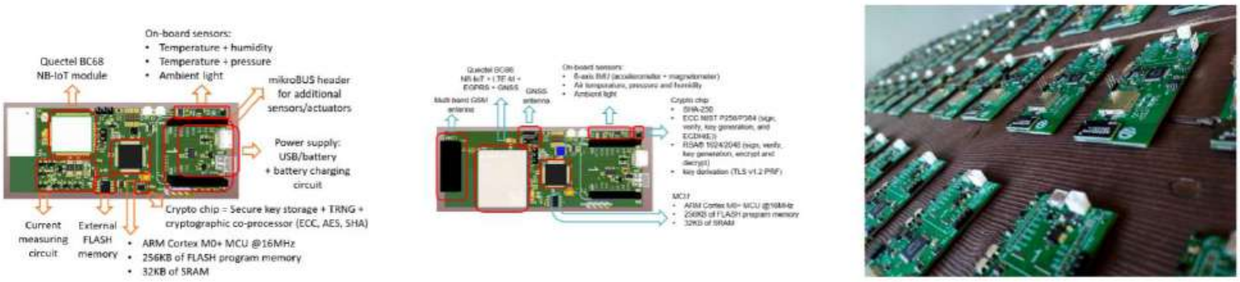

Figure 3. 3GPP NB-IoT device platforms developed at ICONIC

Hardware support: For the development of massive NB-IoT testbed, ICONIC possesses:

- 80 low-power battery-operated NB-IoT devices with temperature, humidity and pressure (THP), and illumination sensors suitable for indoor (e.g., Smart Building) use cases
- 50 low-power battery-operated NB-IoT devices with inertial measurement units (IMU) and GPS modul suitable for outdoor (e.g., tracking) use cases

Devices are connected to A1 mobile operator network providing NB-IoT services. Layout of surrounding macro-cellular base stations is presented in Figure 5, along with the location of Faculty of Technical Sciences (FTN) building where ICONIC centre labs are located.

Software support: For this testbed, we are developing our own firmware that is deployed on microcontroller units (MCU) and we are using vendor-provided loggers to collect rich set of messages exchanged between UE and eNB for the purpose of research, testing and analysis.

Testbed integration: We have tested and verified all the NB-IoT devices and we have run measurement campaigns with the goal of characterizing NB-IoT module energy consuption during different connectivity stages. We have used the testbed deployment is several indoor and outdoor use cases where larger number of NB-IoT devices were be deployed for the purpose of long-term trials, measurements and data collection as we will explain in the examples in the sequel. We are currently experimenting with many trials. For example, a small indoor illumination measurement testbed is set up in our lab as illustrated in the figure on the right-hand side, where 20 devices collect illumination data at a rectangular grid for the purpose of indoor illumination modeling and indoor localisation using visible light.

Figure 4. NB-IoT devices in illumination use case

Figure 5. 3GPP NB-IoT network base stations surrounding FTN building

We are constantly working towards further integration of NB-IoT testbed in order to accommodate requirements for participation in several EU funded projects and to customise the testbed for our own research requirements and data collection needs. The testbed includes several key features:

- Fixed and long-term location of indoor NB-IoT devices for collection of massive scale data sets for future analysis (including design of appropriate casing of devices, including a space for an attached battery, so that they can be easily deployed and relocated if needed, as illustrated in Figure 5)
- Persistent definition of new of use cases for long-term measurements
- Firmware-over-the-Air (FotA) updates of all installed devices
- Establishment of an experimentation platform for on-device (edge) and Cloud machine learning algorithms.

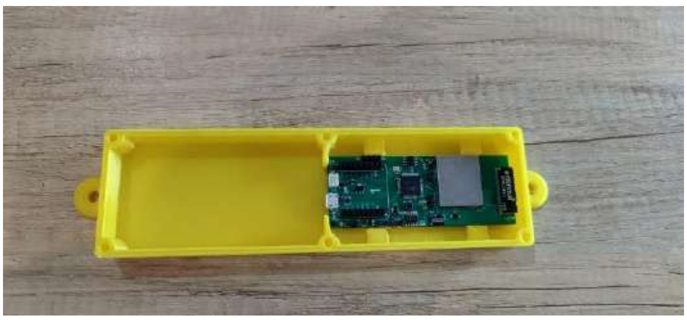

Figure 6. NB-IoT device casing for indoor use cases

Massive IoT solutions for research, demonstration and innovation: After complete integration of the NB-IoT testbed, we deployed it as part of a number of use cases in different EU projects. Examples of various use cases used for demonstration purposes are discussed below:

- <u>NB-IoT device energy consumption monitoring:</u> We implemented a testbed for collecting measurements and training ML models that will track energy consumption of battery-operated NB-IoT devices (for timely maintenance and uninterrupted service). The system trains a neural network based on the radio channel parameters and data packet lengths labelled with measured energy consumption. In inference stage, the system is able to track the device energy consumption based on the recorded channel conditions and packet sizes. The conference and journal publication for this work is in preparation.

- NB-IoT for Smart Logistics: We used the developed testbed in H2020 project C4IIoT where 20 NB-IoT devices are deployed to train unsupervised ML models that learned normal vibrations of containers carried by the trucks during standard logistic transport. In case the container experiences unusual vibrations or overturning, which for some transport goods is unacceptable, the device is able to recognise the situation and flag such a container as the one carrying unusable goods.

Figure 7. NB-IoT device developed for Smart Logistics use cases

The key feature of the above devices is a lightweight ML model derived and based on TinyML framework that is developed, trained and deployed on NB-IoT device ARM microcontroller to perform requested inference tasks. Similar but more powerful methods have also been developed and deployed at the fog level (within mobile operator network) at at an external cloud. This testbed was then used to assess the complete edge-fog-cloud continuum deployment for such a use cases, including the burden and trade offs of shifting data from NB-IoT device towards the cloud, but also, the complexity and energy efficiency of the ML models used at all levels of hierarchy. Our findings have appeared as several conference and journal publications [7], [8].

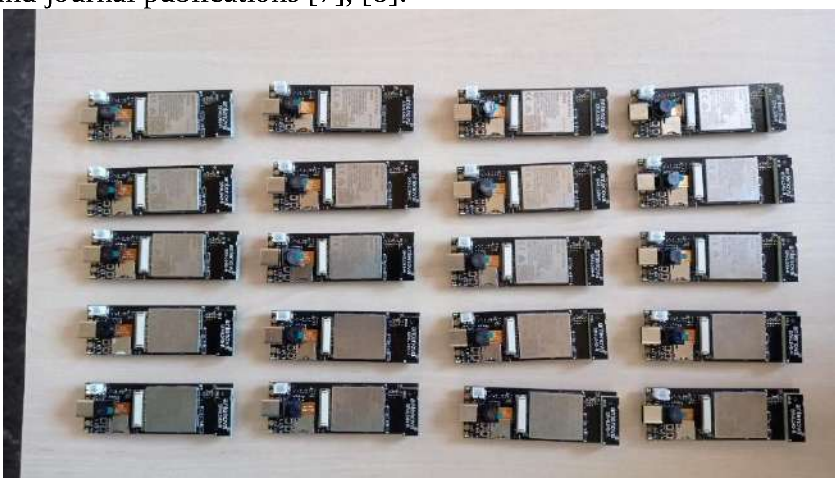

Figure 8. NB-IoT device developed for retrofitting of legacy meters

- NB-IoT for Digit Recognition for Retrofitting Legacy Metering Infrastructure: In this proof of concept project, we expanded our NB-IoT testbed towards supporting device platforms with inexpensive cameras and lightweight on-board ML algorithms for digit recognition. The set of developed devices is illustrated in Figure 8.
- NB-IoT network configuration optimization: NB-IoT network operation can be highly inefficient if the network configuration is not adapted to network traffic. For example, configuration of uplink data channel called NPUSCH (modulation and coding scheme index, repetition factor, number of subcarriers for uplink transmission) and random access channel called NPRACH (number of preambles and channel periodicity) for different coverage extension classes requires careful optimization. Our goal is to set up a scenario which will produce data sets suitable for network configuration learning and optimization.

Exploitation and outreach directions: Main outreach direction is collection and publication of open data sets in combination with production of conference and journal papers. NB-IoT energy consumption monitor has been showcased at 5G IT Hub events and will be considered for further commercialization.

6 UAV-based IoT Communications: Fundamentals and Testbeds

Background: Evolution of mobile cellular networks includes future extension of 5G and beyond networks to include concepts such as cellular-supported vehicular networks (C-V2X) connecting vehicles to network infrastructure and non-terrestrial networks (NTN) integrating low-earth orbit (LEO) satellites into the 5G infrastructure. A new concept that lies in between C-V2X and NTN networks is recently introduced based on UAV-assisted cellular networks. UAV nodes may represent network devices (UEs) or network infrastructure (eNBs and relay nodes). To address the needs of both UAV applications and cellular industry, 3GPP is working on extensions for drone-based communications in 4G/5G networks [9].

6.1 Fundamentals of UAV-Based IoT Networks

System model: We consider a scenario where a group of users are operating in a deep rural environment without line of sight to mobile network operator (MNO) infrastructure. In such rough terrain scenarios, we use the UAV as a network relay to overcome transmission problems. The system model is divided into two logical subsystems, i.e., the fronthaul link and the backhaul link. In the fronthaul link, we have uplink transmission of the wireless access network with *n* radio users simultaneously transmitting to a common receiver placed on the UAV with synchronized transmissions of equal duration. The goal is to determine the expression of the probability that a device signals is reconstructed in the presence of interference under various random access schemes, from which we can easily obtain the throughput of the fronthaul link. When a packet is received through the fronthaul link at the UAV receiver, it can be further relayed through the backhaul link to the MNO basestations. Through the backhaul link, *m* packets are transmitted sequentially per unit time, and *N* channel uses are divided into *m* slots of length *N*/*m*. A finite block length error aproximation is used to evaluate error probability. The goal of the system model is to optimize overall throughput across tandem relay channels. Also, the placement and altitude of the relay UAV are of great importance. MNO base station antennas are usually tilted to the ground to serve ground users, and the relay UAV is usually served only by the side lobes of MNO antennas, therefore angle dependent path loss model is used.

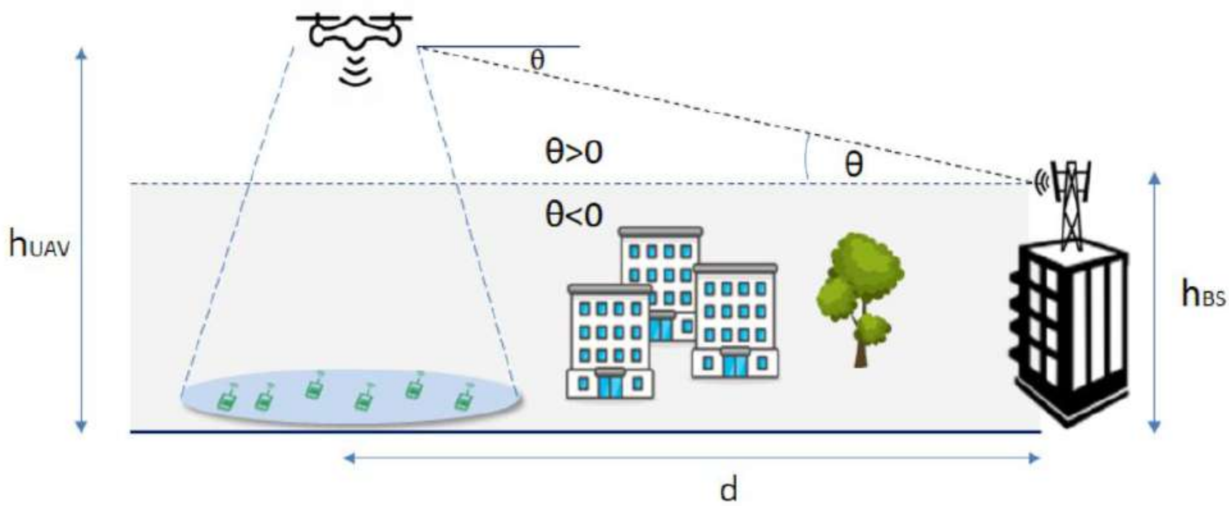

Figure 9. UAV-based massive IoT network system model

6.2 UAV-Based IoT Networks: Testbed and Experimentation

Hardware support: For the development of UAV-based Cellular IoT testbed, ICONIC possesses:

- Drone DJI Matrice Pro 600 with equipment carrier that can carry USRP SDR, mini PC and a battery pack sufficient for about 25 minutes of hovering time,
- Several small DJI drones (Mavic 2, Phantom 2)
- LoRa and NB-IoT devices, USRP SDR and mini PC equipment

Software support: For drone-based communications, we use commercial off-the-shelf 4G and 5G modems, NB-IoT or LoRa devices, custom-designed NB-IoT devices, and deploy a custom programmed firmware on these devices. We also use mini PCs combined with USRP SDRs in combination with OAI, srsLTE or similar open-source software to set up a full 4G/5G network (both eNB/gNB and EPC/5GC) on the drone. Two drones (large and small) equipped with various communication equipment are illustrated in the figure below, where the large drone carries a network on the drone, while the small drone acts as a mobile UE NB-IoT device.

Figure 10. Large DJI Matrice Pro 600 drone (left) and small DJI Mavic 2 drone (right)

Testbed integration: Figure 10 illustrates our UAV-based testbed. The large drone is able to carry necessary wireless equipment and can be successfully connected to mobile operator macro-cellular base stations either through COTS 4G LTE interface (LTE modem) or via COTS or custom-designed NB-IoT devices. The large drone can also carry full SDR-based configuration, including Intel NUC i7 mini PC and USRP SDR B210 with all the necessary components. With this approach, we can run OAI or srsLTE software on the drone (both eNB/gNB and EPC/5GC software) making the drone an aerial 4G or 5G cell. With such an approach, it is possible to connect COTS 4G/5G UE phones, 4G/5G evaluation board modems as well as laptops running OAI/srsLTE UE code with attached USRP SDR radio. Thus large drone can provide 4G LTE or 5G NR access in a limited area to other devices on the ground in its vicinity. OAI also supports NB-IoT, however, this code is still under development and is not stable, so until the present moment, we were not able to send data from NB-IoT devices through OAI NB-IoT eNB attached to the drone. Besides creating and deploying 4G or 5G network on the drone, we attached COTS LoRa gateway on the drone and were able to connect LoRa UE devices, either ground based, or attached to another small drone that was exploring the terrain below the large drone.

Ongoing and future testbed improvements: Although our UAV-based communication testbed is already operational and has been tested, there are many improvements that is under implementation. Below, we list several most important ones:

- Although we tested 4G LTE and 5G NR network-on-the-drone in lab environment, we need to test it in real-world outdoor deployment with connected COTS UE that uses bandwidth-hungry services like video transmission.
- We would like to decrease the size of our setup, switching from miniPC to RPi 4 as a computation platform, and from USRP B210 to smaller SDR platforms such as LimeSDR.
- Our next step is in deployment, evaluation and testing of drone-to-drone communication and drone-to-vehicle communication via 4G LTE C-V2X sidelink protocol.
- So far, our focus was on communication between drones and infrastructure. Our plan is to expand this work to other related directions, e.g., remote drone control via 4G/5G radio interface (i.e., gaining experience with programming drone controllers) and device localisation using drones.

Massive IoT solutions for research, demonstration and innovation: There are a large number of use cases one can envisage using UAV-based extensions for cellular IoT or broadband connectivity. During INCOMING project, we considered a large number of such use cases. Here, we provide description of use cases we are in the process of development:

- UAV-based NB-IoT/LoRa cell design and deployment: Although the initial version of the setup was demonstrated, our current goal is to advance the research, measurements and modelling that would optimize UAV placement for maximum NB-IoT system throughput and connection density.
- Rural area data mule: Data gathering using UAVs for remote IoT fields is one of the most relevant applications of drone-based IoT systems. We integrated and demonstrated UAV-based data gathering of remote wireless sensor network. This has been done by implementing IEEE 802.15.4 gateway integrated at the drone and appropriate MAC protocol for remote data gathering.
- Digital shepherd: This application is original vision of the solution presented at the IEEE VTS UAV innovation challenge. The goal is to use a small drone equipped with a video camera to monitor herd of animals in deep rural area by using computer vision object detection algorithms to count the animals in the herd. This number is periodically communicated via a large drone to the cellular network and cloud servers. Our plan is to integrate a complete scenario and use it as a demonstrator of deep rural use cases as part of the Marie Curie Staff Exchange project REMARKABLE that has just started.
- Drone as a water quality sampler: Following the successful set up of UAV testbed as part of INCOMING project, we received a new grant by Serbian Science Fund for the project proposal entitled REWARDING on remote water quality monitoring and intelligence. Within this project, drones will be used as water quality samplers, and also, as a communication and relaying platform for sensor-equipped smart water buoys.

Publications, exploitation and outreach directions

Main outreach direction during INCOMING project was in the domain of testbed integration and demonstration, collection and publication of open data sets, demo conference and journal papers, and further project funding proposals that build on top of what has been done in the domain of UAV-based communications in INCOMING project (two successful project applications: Horizon Europe REMARKABLE Marie Curie Staff Exchange and Serbian Science Fund project REWARDING, and one unsuccessful DRASTIC Marie Curie Doctoral Network). Several UAV-based use cases have also been showcased at 5G IT Hub events at several occassions (see footnotes for links to relevant youtube videos) and will be considered for further commercialization.

IEEE Vehicular Technology Society UAV Challenge: During 2020, a team of PhD students from ICONIC: Srđan Šobot, Dušan Bortnik, and Vladimir Nikić, teamed up with a PhD student Brena Lima from University of Lusofona, Lisbon, Portugal, under supervision of Dr Milan Lukić and Prof. Dejan Vukobratović from ICONIC and Prof. Marko Beko from University of Lusofona, to participate at IEEE Vehicular Technology Society UAV Innovation Challenge[2]. The solution named “Two-tier UAV-based LP-WAN network for coordinated missions in deep rural environment” won the first stage of the competition[3]. The second phase included demonstration of the solution in a real-world rural environment without cellular network coverage. The team won the second (final) stage of the competition[4].

During the CIoT conference held in Lisbon, Portugal, in March 2023, a team of PhD students presented a paper where a two-tier LP WAN architecture for deployment of IoT services in deep rural environments without a cellular network coverage is proposed, designed, deployed and demonstrated. The proposed system is implemented in two scenarios (Tier 2 LP WAN being either LoRa or NB-IoT) and demonstrated in two real-world settings (urban and rural). The testbed and experimentation platform is presented through samples of radio link condition measurements. The proposed two-tier LP WAN network scenario is suitable for various agricultural, forestry, and environmental applications, such as livestock or wild animal monitoring.

[2] https://events.vtsociety.org/vtc2020-fall/authors/vts-innovation-challenge-for-students/
[3] https://www.youtube.com/watch?v=QU0vkbEcO1w
[4] https://www.youtube.com/watch?v=3_Px0hAjpVE

7 OWC-based IoT communications: Fundamentals and Testbeds

Background: The current wave of digital transformation is being driven by a growing need for enhanced wireless connectivity, most notably through adoption of the Internet of Things (IoT) paradigm in modern smart infrastructures. IoT is an innovative technology that enables the seamless integration of physical and digital realms by connecting smart objects that can be uniquely identified. Since the IoT communications are typically characterized by sporadic and unpredictable device activity involving short data exchanges, a cost-effective approach to support such communication patterns over a shared wireless medium is to use random access (RA) protocols, which allow for a more efficient use of the time-frequency resources. Slotted ALOHA (SA) is a well-established RA scheme, serving as the basis for wireless access solutions implemented in many of the modern commercial systems.
Spectrum shortage is promoting a surge of research aimed at exploiting higher frequency bands for wireless communications, ranging from millimeter-wave, via terahertz to optical (infrared or visible) bands. Each of these possibilities appears to be well suited for specific environments and applications, and the ongoing research trends point towards a combination of strategies to meet the requirements of ever-increasing number of IoT devices.

The domain of optical wireless communications (OWC) is gaining an attention as a complementary technology able to offload massive wireless traffic in indoor environments, relaxing the challenges posed by the spectrum crunch experienced by current RF-based technologies. OWC is considered an appropriate candidate to meet the demands of 5G and beyond 5G networks due to its desirable properties, including wide and license-free spectrum availability, high data rates, low cost, and easy deployment. Due to desirable properties, the OWC can be seen as a promising alternative to RF for IoT technologies, especially in RF-restricted areas where the light-emitting diodes (LED) can be safely used as wireless transmitters

The OWC-based IoT deployment scenario assumes an indoor space comprising large and unobstructed areas (e.g., a warehouse or an open-plan office), where a large quantity of devices collects, process and send data to a number of access points (APs). In such situation, the use of RF links could lead to an intolerable level of interference and a high probability of packet loss due to collisions. However, transmission technologies based on OWC can help to tackle these challenges, despite their limited coverage. In fact, by resorting to OWC links, the interference across walls is eliminated, and a small scale indoor cellular network could be designed to cover the whole space with a minimal coverage overlapping, thus maximizing the overall throughput.

Indoor OWC-based IoT communications

Indoor OWC-based IoT communications comprise a communication scenario in which a total number of IoT devices equipped with OWC transmitters contend to access a common OWC AP. The transmitting devices are uniformly placed on a horizontal plane, while the OWC AP is located at the ceiling at a fixed location (see Fig. 11). The SA protocol is used for uplink transmissions. Each IoT device is active for transmission with a certain probability in every slot, independently of its activity in other slots and of the activity of other devices during the same slot period.

The IoT devices use IR LED sources, while the OWC photo-detector receiver performs direct detection of the arriving light intensity. The described OWC based IoT architecture is simple, low cost and suitable for the low data rate requirements of short-range indoor IoT systems. Our framework addresses the scenario envisaged by IEEE 802.15.7-2018 standard for short-range low-speed OWC IoT systems, within the proposed PHY II type architecture that uses IR signals with OOK format for both infrastructure (AP) and mobile (IoT user) devices.

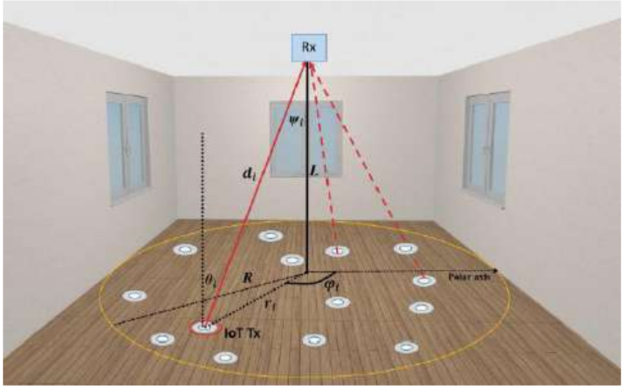

Figure 11. OWC-based IoT system model.

We analyse an architecture for future IoT based on short-range OWC technology and design an access scheme for an OWC-based IoT indoor network. The proposed scheme is analysed in the terms of the SINR statistics of the accessing users and used to evaluate its performance. The error and the coding rate characterizations are based on the finite blocklength (FBL) performance analysis for OWC-based IoT systems. From the SINR statistics the error probability affecting the captured data packets, protected by an appropriate channel code, is derived, thereby determining the system performance. Building up on the physical layer characterization, our work presents the analysis of the overall system throughput and the reliability in terms of the outage probability. For more details, check the conference and journal publications [10] and [11].

Underwater OWC-based IoT communications

Since about 70% of the Earth surface is covered by water, the IoT applications have been extended to underwater environments, named Internet of Underwater Things (IoUT). The IoUT framework, mostly deployed as a part of the Smart Ocean, represents a smart network of the intelligent, interconnected underwater objects, such as sensor nodes, autonomous underwater vehicles (AUV), boats, gliders, divers, and similar. Unique characteristics of the underwater medium result in the different models and designs of IoUT compared to the classical land-based IoT systems.

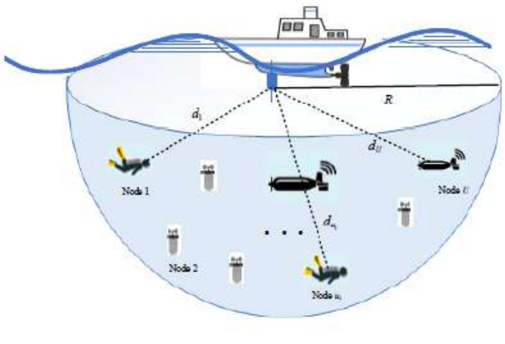

Figure 12. OWC-based underwater IoT system model.

One part of research is devoted to a novel design of future OWC-based IoUT systems. As presented in Figure 12, the system observes 3D setup, with the IoUT devices located within a half-sphere centred at the AP. OWC AP is fixed to the bottom of a floating object on the water surface level. The uplink communication based on SA with capture effect is considered, meaning that the OWC AP will try to decode the packet even if more than one user is active in a slot. The main goal of the proposed setup is to investigate how SA with capture affects the system reliability and throughput in the underwater conditions.

The SINR statistics, which takes into account specific underwater medium, is utilized to analyse the overall system performance, including reception reliability and the system throughput. The trade-offs between the performance and the IoUT system parameters is observed, which can help us to obtain valuable insights for design of an SA-based solution for an OWC based IoUT [12].

Two-tier OWC/RF IoT communications

Due to the widespread installation of RF communication systems, their combinations with indoor OWC systems are easily envisioned, named two-tier OWC/RF systems [13]-[17].

One part of research [13] is related to design of the mixed RF-VLC relaying systems suited for interference sensitive mobile applications. In these application scenarios, the end-user is assumed to be on a vehicle which is in dynamic movement (e.g. emergency ambulance, trains, airplanes or upcoming self-driving electrical vehicles), while the indoor environment is RF unfriendly, i.e., strong electric field intensity induced by some RF frequencies can interfere with electronic equipment resulting in critical data loss. Analytical framework for the performance evaluation of the RF-VLC relaying system is provided, which further help us to observe the effects of both RF and VLC channel parameters on system performance.

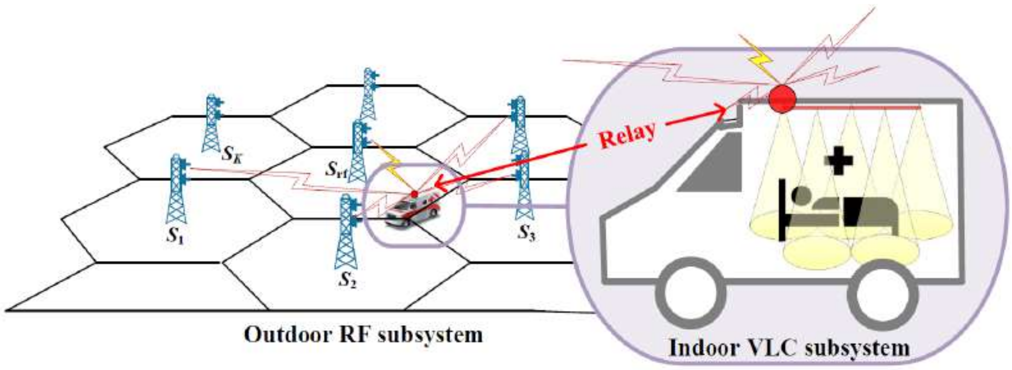

Figure 13. Dual-hop mixed RF-VLC communication system for interference sensitive applications.

To relieve pressure from conventional RF-based LP WANs, OWC have been recently considered as an emerging complementary technology, resulting in hybrid OWC/RF massive IoT network based on a novel two-tier multi-rate SA system design.

One type of considered two-tier OWC/RF system considers that the first tier is a single large indoor OWC IoT system with a large number of indoor OWC APs (which act as relays), while the second tier, between the relays and a base station, represents the long-range RF transmission based on low-power wide area network such as LoRaWAN and occurs outdoors, as presented in Fig. 14 [14]. The next step was to observe the two-tier OWC/RF system where the first tier comprises a collection of isolated indoor OWC IoT networks connected to a network infrastructure via the second-tier outdoor RF-based LP WAN, see Fig. 15 [15]. Additionally, this work for the first time explores that the SA protocol at the LP WAN tier operates at M times higher slot rate relative to the OWC tier.

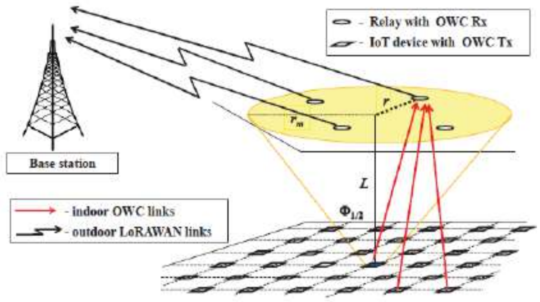

Figure 14. Two-tier OWC/RF IoT communications with multiple receivers.

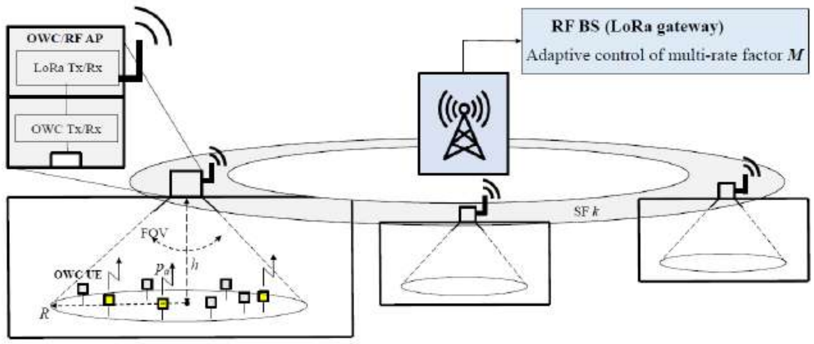

Figure 15. Two-Tier OWC/RF-Based IoT Network.

Furthermore, hybrid two-tier OWC/RF system which combines a massive collection of indoor OWC-based IoT small cells with the outdoor RF-based mMTC network was investigated [16], [17]. More precisely, the first tier comprises a collection of isolated indoor OWC IoT networks connected to a network infrastructure via the second-tier outdoor RF-based LP WAN, as presented in Fig. 16.

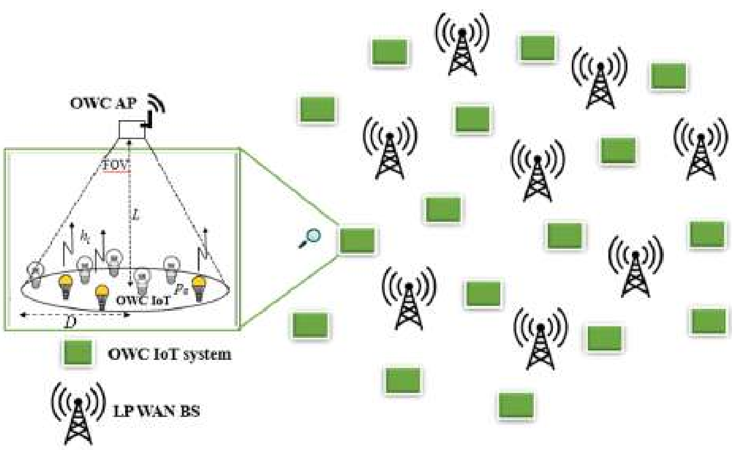

Figure 16. System model of a wide-area hybrid OWC/RF network.

Summary

This report provided an overview of the outcomes of the research and development mini-projects during the INCOMING project. It identifies the most important lines of fundamental research and testbed developments whose target is to develop research infrastructure and capacities of ICONIC centre in the future, bring its staff closer to innovation activities and increase visibility through real-world showcases and demonstrations. The above described testbed capacities evolved towards a set of promising use case demonstrators that would provide basis for various dissemination and outreach activities, such as publication of conference and journal papers, presentation of demos at various public events, potential spin-off of startup companies and tighter integration with regional industry in joint research and development projects (examples of which are already presented in this report). In this sense, coordinated and coherent activities of INCOMING project, as detailed in D2.3 and D3.3, will further increase visibility of ICONIC centre and make it a desireable partner in future national, EU or industrially-funded projects.

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