NATIONAL UNIVERSITY OF SCIENCE AND TECHNOLOGY POLITEHNICA BUCHAREST

Doctoral School of Electronics, Telecommunications and Information Technology

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Ph.D. THESIS
SUMMARY

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PIONEERING OPEN 5G-ENABLED APPLICATIONS FOR SOCIAL IMPACT AND TECH FOR GOOD: FROM RADIO COMMUNICATIONS OPTIMIZATION TO LIFE-SAVING INNOVATIONS

PIONIERATUL APLICAȚIILOR BAZATE PE 5G OPEN PENTRU IMPACT SOCIAL ȘI TEHNOLOGIE PENTRU BINELE COMUN:
DE LA OPTIMIZAREA ÎN DOMENIUL RADIOCOMUNICAȚIILOR LA INOVAȚII SALVATOARE DE VIEȚI

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Chapter 1

Introduction

1.1 Presentation of the field of the doctoral thesis

The introduction of 5G technology enables innovative applications like autonomous driving, remote robotics control, and tactile internet. However, these advancements present significant challenges, requiring network infrastructure to handle extremely low latencies of sub-ten milliseconds and availability levels comparable to fixed networks.

1.2 Scope of the doctoral thesis

The primary objective is to explore and demonstrate the practical implementation and advancement of cutting-edge radio communications technologies, particularly focusing on 5G networks, software-defined radio (SDR) systems, and drone-integrated solutions.

1.3 Content of the doctoral thesis

The organisation of the thesis is highlighted in Figure 1.1.

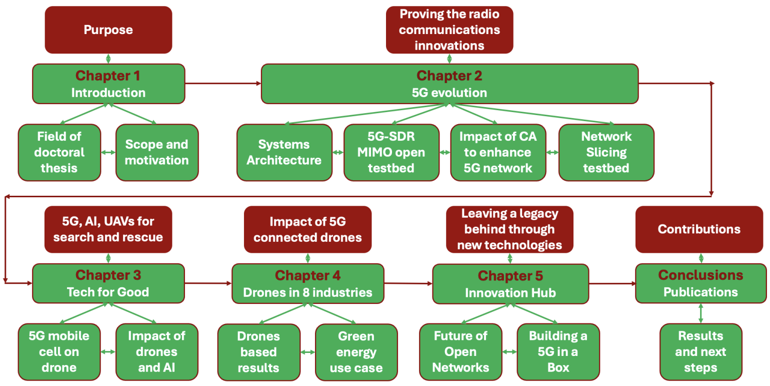

Figure 1.1 Organisation of the paper

Chapter 2

Enhancing 5G ecosystem with new testbeds: theoretical concepts and implementations

2.1 Architectural and technological concepts and visions specific to the new 5G standard

2.1.1 Mobile communication systems evolution. 5G technology and cognitive radio: Preliminaries

In recent decades, mobile communication networks have undergone significant transformations. Each generation (G) of mobile telephony is defined by notable shifts in parameters such as the technologies employed, system architecture, capacity, speed, frequency bands, and latency. These generations introduce unique standards, procedures, and features that differentiate them from those that came before [1].

5G technology

Within the standardization processes for 5G networks, three initial scenarios have been proposed to comprise the design guidelines for 5G technologies, namely: enhanced mobile broadband (eMBB), ultra-reliable and low-latency communications (URLLC), and massive machine-type communications (mMTC) [2] [3]. Thus, eMBB can provide throughput up to 1 Gbps, mMTC brings advantages for IoT connected devices, while URLLC will focus on reliability on the order of 99.999% and latency in terms of milliseconds for real-time applications [2].

To meet the requirements in these scenarios, the evolution of 5G will mainly focus on three aspects: the allocated frequency spectrum bands, the new technologies used, and the 5G core network [2], respectively.

Regarding the frequency bands allocated for 5G, the spectrum with frequencies below 6 GHz will be used in the first years of the implementation of the new technology [4]. In turn, this spectrum is split in different bands with frequencies below 1 GHz and those with frequencies between 1-6 GHz [2]. Within the first category, a significant role will be played by the 4G 700 and 800 MHz bands, as these bands are expected to be responsible for IoT services and urban and rural [4] coverage, due to the fact that at these frequencies , the attenuation of the signals is less pronounced. The second category, represented by frequencies between 1 and 6 GHz, provides an optimal balance both for coverage and data throughput in 5G use cases [2].

At present, mobile communication networks are gradually transitioning from 5G Non-standalone (meaning both 4G and 5G use the same core network, with the radio access part being new, 5G-type, with smart antennas, massive-MIMO access systems, allowing many more users to connect simultaneously) to 5G Standalone, a dedicated core network.

2.1.2 5G architectural visions

5G networks are engineered to possess exceptional adaptability and extensive programmability throughout their whole infrastructure, enabling them to accommodate various applications and services, as well as take into account factors such as location and context. These signify:

- Increased capacity, efficiency, and spectrum utilization in the radio network.
- The 5G network segments are undergoing a transformation where they are becoming more flexible and programmable, allowing for greater adaptability and versatility.

The 5G architecture (Figure 2.3) facilitates novel commercial prospects by fulfilling the demands of a diverse array of use cases.

Visions on physical and infrastructure resource control

The core concept of 5G is to create a unified and versatile network environment that integrates multiple radio access technologies with wired or wireless solutions, connecting a high number and categories of devices and people [6]. These resources are located in data centers. MEC offers IT and cloud capabilities directly within the RAN network, close to mobile users, whereas regional or large-scale data centers provide similar services.

Network softwarization, integral to 5G, utilizes Software-Defined Networking (SDN) and Network Function Virtualization (NFV) to trigger the innovation. SDN decouples the control plane from the data plane, with a centralized controller managing the resources of the network, while NFV enables software functions on standard hardware through

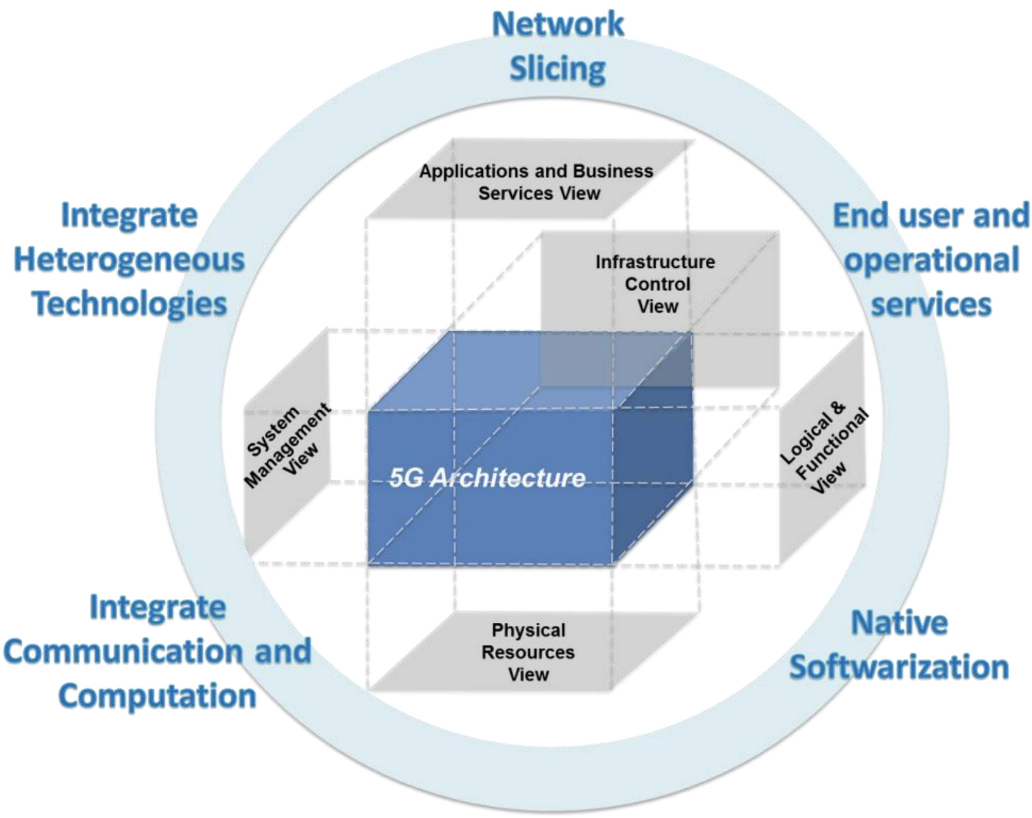

Figure 2.3 5G architectural visions [5]

virtualization. These approaches enhance flexibility, resource efficiency, scalability, and simplify infrastructure, enabling seamless end-to-end services [5].

2.1.3 Dynamic spectrum sharing (DSS)

Dynamic spectrum sharing (DSS) is a crucial technological advancement in wireless communication, particularly evolving from 4G to 5G New Radio (5G NR). Through DSS, 4G and new 5G services can be used simultaneously using the same frequency band. This is achieved by dynamically allocating spectrum resources controlled by the demand and network parameters, which enhances spectral efficiency and facilitates a more seamless deployment of 5G networks. By leveraging DSS, network operators can maximize the use of their existing spectrum assets, ensuring backward compatibility with 4G devices while gradually introducing 5G capabilities without requiring additional spectrum licenses. This approach significantly accelerates 5G rollout by allowing the coexistence of both technologies, optimizing network performance, and reducing deployment costs.

2.1.4 Conclusions

In this section, a number of requirements have been discussed from a business perspective, such as minimizing provisioning time, enabling multi-tenancy of the network, and from a technical perspective, such as the use of different spectral bands operating in ultra-dense environments, with very low latency for services at the highest availability. SDN and NFV will have significant significance, while their suitability in various domains (access, transport, core) is anticipated to have distinct implementations. In this adaptable setting, it is necessary to reexamine subjects like network administration and security and implement novel procedures.

2.2 Contributions on spatial multiplexing MIMO 5G-SDR open testbed implementation

2.2.1 Introduction

The aim of this section is to suggest an open testbed solution for conducting practical studies on 5G New Radio. This will involve the use of Software-Defined Radio (SDR), determining the best parameter settings, evaluating vendor equipment, conducting realistic tests on radio equipment behavior, and ensuring the platform can be expanded to meet future technical requirements.

2.2.2 Theoretical prerequisites for MIMO SDR testbed development

MIMO channel model - statistical analysis

In order to characterize SISO systems (single input, single output) (SISO), it is necessary to take into account the spread delay and the Doppler effect. The first can be understood as the discrepancy between the time when the earliest multicast component is received and the time when the last significant multicast component arrives. This concept is employed to describe the radio channels. Doppler displacement is the phenomenon where the motion of a user determines a frequency change of the broadcast signal when moving at a certain speed. Signals traversing various pathways and regions may exhibit distinct Doppler displacements, which correlate to different phase shifts [7].

Description of MIMO channel

This type of channel must be described for all antenna pairs, transmitter-receiver. For M broadcasting antennas and N receiving antennas, the MIMO transmission channel can be represented by an $N \times M$ size matrix shown in Eq. 2.1 [7].

$$\mathbf{H}(t,s) = \begin{bmatrix} h_{11}(t,s) & \dots & h_{1M}(t,s) \\ \vdots & \ddots & \vdots \\ h_{N1}(t,s) & \dots & h_{NM}(t,s) \end{bmatrix} \tag{2.1}$$

Each element $h_{nm}(t,s)$ is the variation in pulse response in time between the mth input of the transmitting antenna and the nth output of the receiving antenna. Each pulse response is the cascaded effect of the transmitting antenna, the propagation medium, and the receiving antenna. The spatial and temporal correlation between the signals received at different antennas is reflected in the matrix elements.

MIMO channels can be categorized as either physical or analytical. Physical models are constructed using either geometric principles derived from physical theory or by utilizing physical measurements. These are specialized for a certain sort of environment or region (urban, suburban, and rural) and are employed in the process of network planning. Analytical models are agnostic to the specific physical implementation and are commonly employed for system development, comparisons, and testing purposes. The MIMO channel matrix was utilized to construct the MIMO channel model block in GNU Radio.

Signal detection for multiple-input multiple-output systems employing spatial multiplexing

Various detection approaches exist for MIMO systems, including ML (maximum-likelihood), which necessitates computational resources beyond the capabilities of most practical systems. In order to simplify the intricacy of MIMO detection methods, equalization techniques such as zero-forcing (ZF) and minimum mean square error (MMSE) can be employed.

The ML detector is the optimal choice for minimizing the likelihood of error. Nevertheless, the implementation of this method poses challenges in practice due to its intricate complexity. The findings in this work are derived from the utilization of ZF and MMSE algorithms, which demand lower processing resources.

Receiving data that is transmitted in a sequential manner over a scattering medium is a complicated process because of the occurrence of inter-symbol interference (ISI).

MIMO systems employing spatial multiplexing achieve higher data transmission rates compared to systems utilizing spatial diversity. Nevertheless, the process of spatial demultiplexing or signal identification during reception poses a challenging endeavor for MIMO systems that employ spatial multiplexing (Fig 2.7).

Consider a MIMO system of N_R receiving antennas and N_T transmitting antennas. The matrix $\mathbf{H}$ is defined as the channel matrix with the element h_{ji} representing the channel gain between the transmitting antenna i and the receiving antenna j (where $j = 1,2,\dots,N_R$ and $i = 1,2,\dots,N_T$). The data from a spatially multiplexed user are

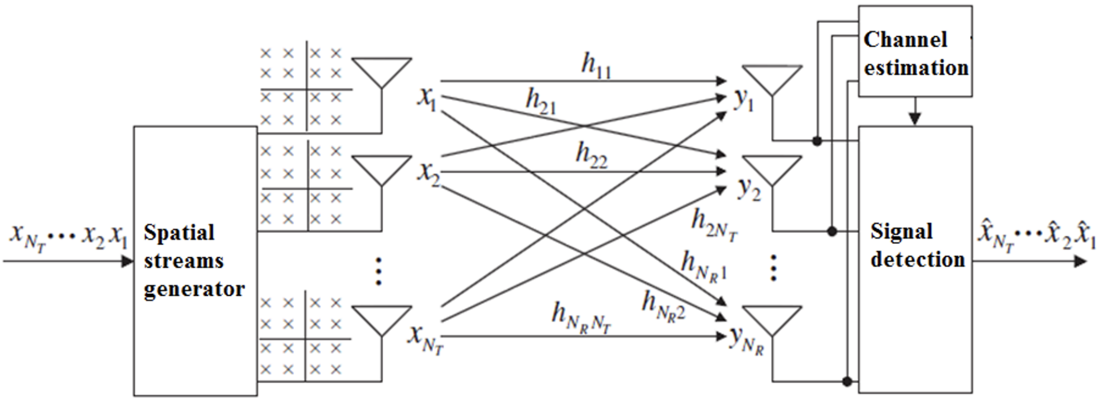

Figure 2.7 Spatial multiplexing MIMO system [8, 9]

represented as $\mathbf{x} = [x_1, x_2, \ldots, x_{N_T}]^T$, and the received data $\mathbf{y} = [y_1, y_2, \ldots, y_{N_R}]^T$, where x_i and y_j represent the signal transmitted from the antenna i and the signal received at the antenna j, respectively. The received signal can be expressed as:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{z} = h_1 x_1 + h_2 x_2 + \cdots + h_{N_T} x_{N_T} + \mathbf{z}$$

where $\mathbf{z} = [z_1, z_2, \ldots, z_{N_R}]^T$ represents Gaussian white noise with variance σ_z^2 at the receiving antenna j, and $\mathbf{h}_i$ represents the i-th column vector of the channel matrix $\mathbf{H}$ [9].

A Matlab implementation was constructed for this research to compare the bit error rate (BER) of a 2×2 MIMO system using the two proposed detection algorithms. The comparison is displayed in Figure 2.8.

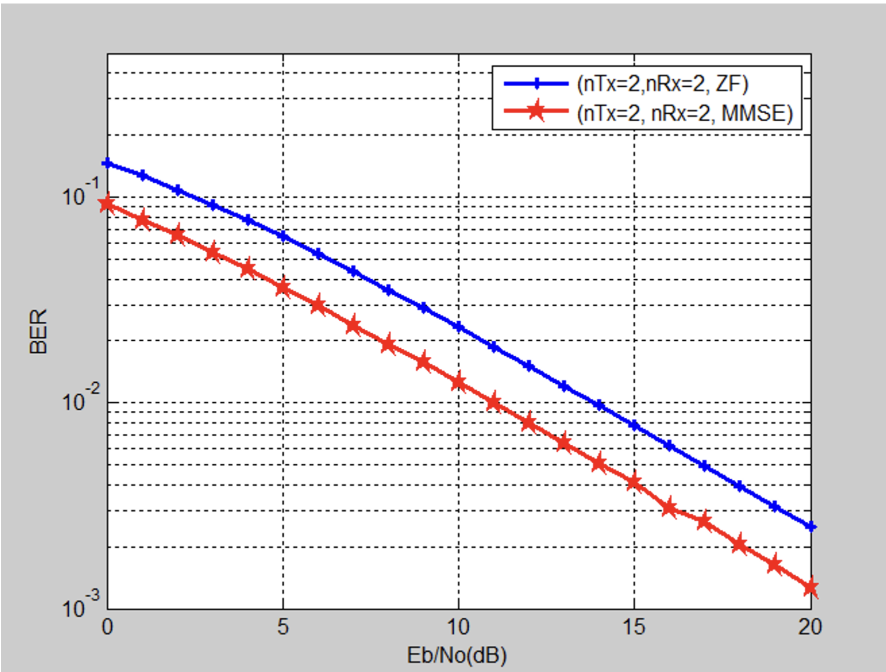

Figure 2.8 BER for 2 x 2 MIMO system (ZF and MMSE) [8]

The graph shows that compared with Zero Forcing detection, at a 10^{-3} BER, MMSE detection has an improvement of 3 dB.

For the real-life tests presented in the following sections, ZF and MMSE detection algorithms were implemented and used.

2.2.3 Testbed setup approach

To develop a SDR platform for integrating MIMO technology, both a software and hardware testbed were deployed. The open-source software GNU Radio [10] was utilized, known for its wide range of applications, particularly in SDRs.

The purpose is to analyze using the test platform built with USRP N210 and WBX/X-CVR2450 submodules, the 2x2 MIMO system, shown in Figure 2.9.

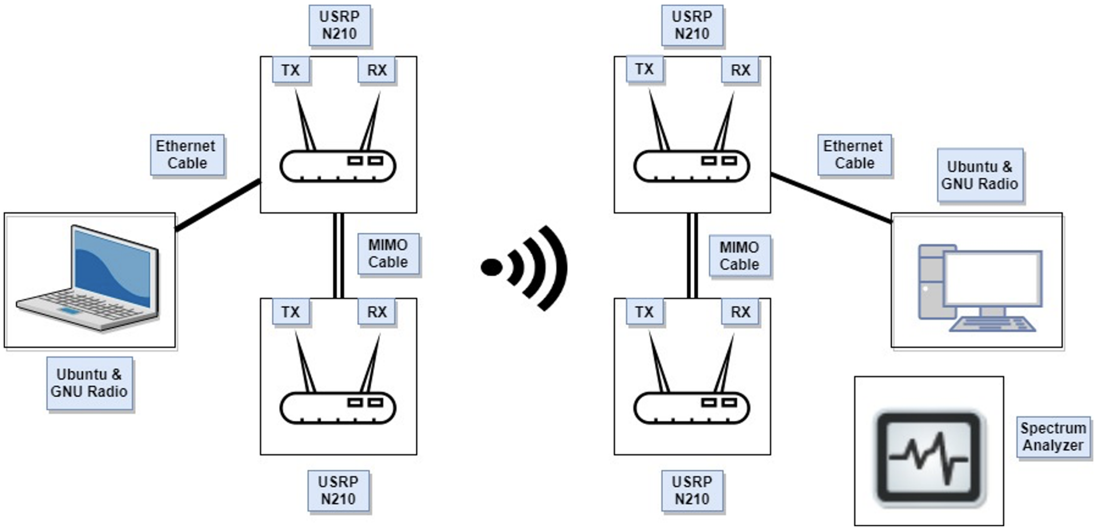

Figure 2.9 Testbed block diagram [8]

The chosen development environment was GNU Radio Companion, in which transmission and reception were implemented (Figure 2.10.

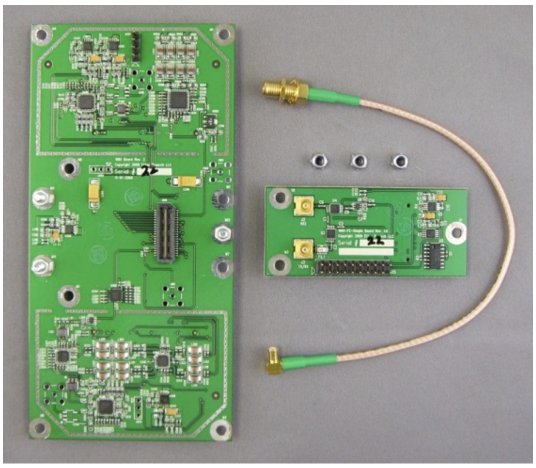

Figure 2.10 WBX submodule [8]

To achieve the desired setup, two USRP N210 boards, each equipped with a WBX transceiver module, were utilized. The operating frequency was set to 2 GHz. Each WBX module includes two antennas corresponding to the selected frequency band. It is crucial that at least one USRP board has a Jackson GPS module installed, as the program execution routine will check for its presence, even if the antenna is not connected. Once all hardware connections have been made on the USRP boards, they can be powered with a DC voltage of 6 V.

Only one antenna on each board is able to transmit data. The second one is for receiving data, to create a duplex communication system (Figures 2.11 and 2.12).

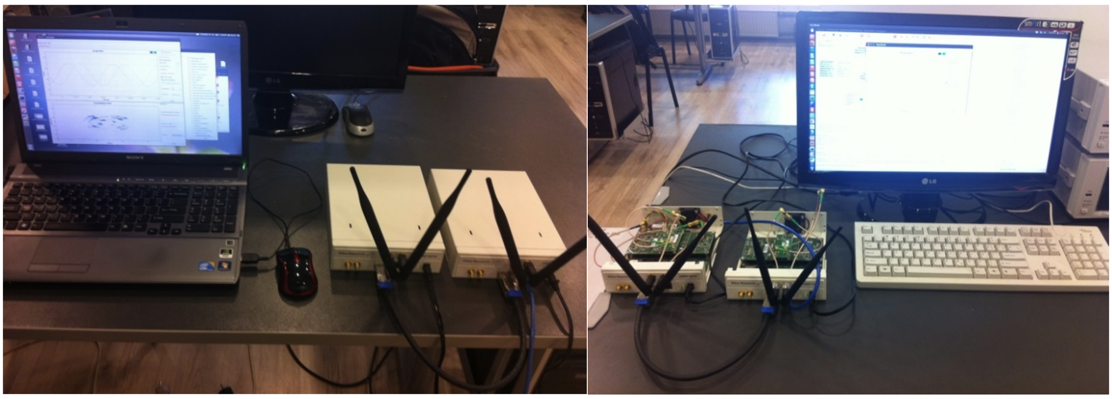

Figure 2.11 Transmission and reception 2 x 2 MIMO [8]

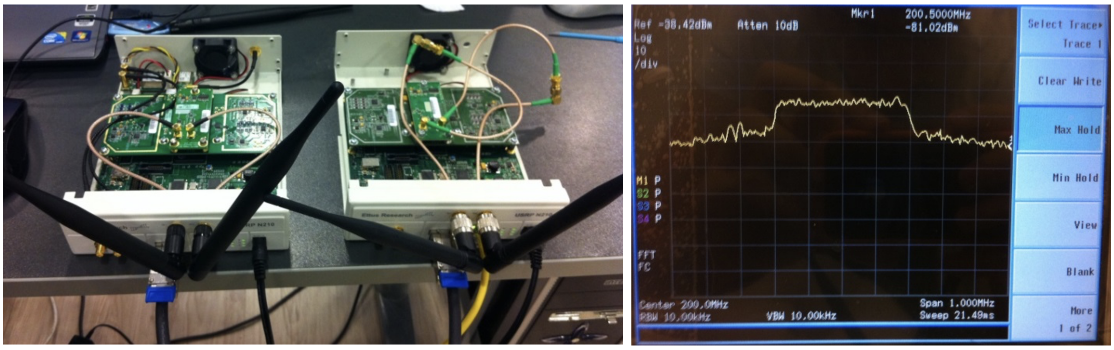

Figure 2.12 OFDM live spectrum on spectral analyzer [8]

2.2.4 Preliminary experimental results for MIMO 5G ready SDR system in GNU Radio

To observe the maximum capacity and error rate of a MIMO channel utilizing two transmitting antennas and two receiving antennas, two separate transmission paths were modeled in GNU Radio. This was done by using OFDM-modulated random data sources, transmitted through a Gaussian white, additive, virtual noise channel. After demodulation, the received data was compared to the transmitted data using an error rate calculation block. To determine the error rate of the entire 2x2 MIMO channel, the arithmetic mean of the two parallel error rates was calculated, and the results were stored in a file. In Figure 2.13, OFDM modulated signal spectrum was captured. Next, the components in time domain, phase (I) and quadrature (Q) can be observed.

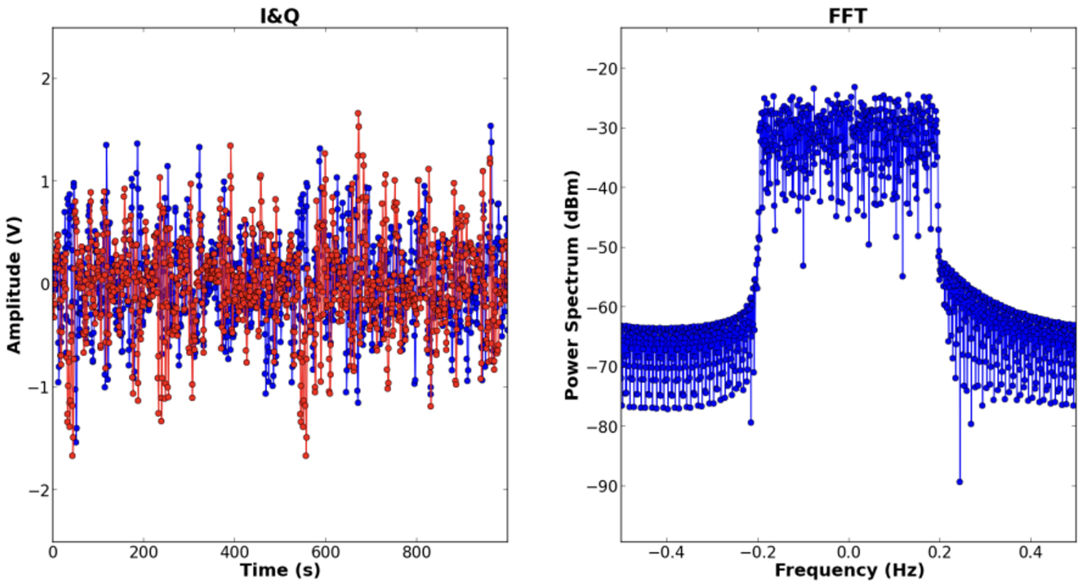

Figure 2.13 Spectrum of OFDM modulated signal - phase and quadrature components [8]

Depending on the number of tones used, the spectrum of the OFDM signal may appear narrower or wider, shown is Figure 2.14.

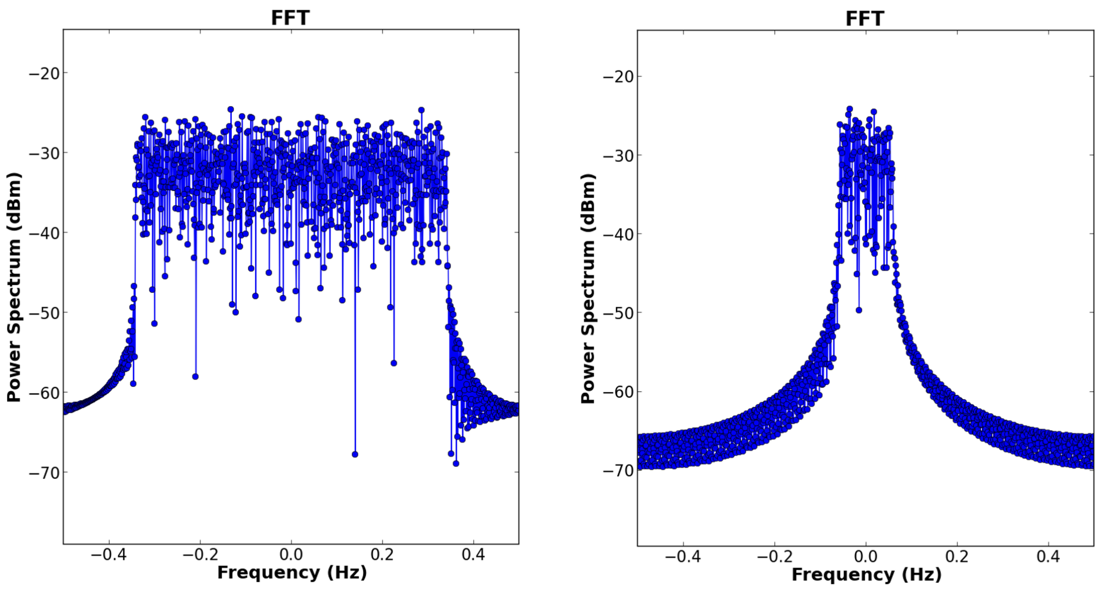

Figure 2.14 OFDM spectrum, 350 tones vs. 50 tones [8]

For each receiving antenna, two additional blocks were introduced: one to remove the OFDM-specific cyclic prefix and another to apply the FFT transform. At this stage, a Zero-Forcing or Minimum Mean Square Error (MMSE) detection algorithm can be applied using either a Python script or Matlab.

Data transmission capabilities test

The data stream must be subjected to an OFDM modulation process, which has a 128 prefix, a FFT window length of 512 samples, and the modulation of the symbols

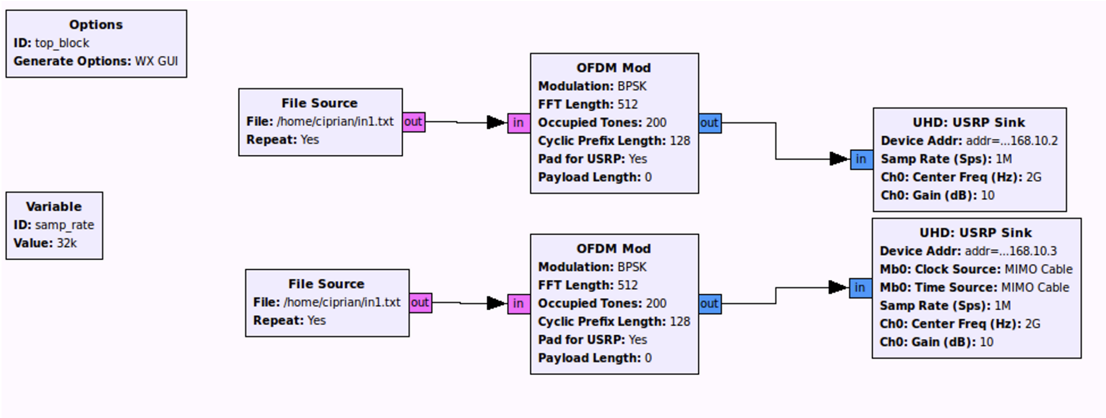

Figure 2.15 Block selection for transmission signal graph [8]

is BPSK. In order to transmit them with broadcasting antennas, USRP sink blocks are needed. The information is sent to the block chain of 2 x 2 MIMO system, previously presented. After the detection and the demodulation process is performed, the data was stored in “out.txt” file and the results shown in Table 2.2 were obtained.

Table 2.2 Packet transmission statistics for different modulation schemes [8]

Modulation	**Number of sent packets**	**Number of received packets**	**Number of good packets**	**Packet loss rate**	**Errored packets rate**
BPSK	655	653	644	0.31%	1.68%
QPSK	655	641	447	2.14%	31.75%
16QAM	655	580	379	11.45%	42.13%

BPSK is the most error-resistant modulation technique, but it has the slowest transmission speed, taking 8.371 seconds to complete. QPSK (Quadrature Phase Shift Keying) is a modulation technique that introduces significant faults. In laboratory circumstances, the least powerful modulation was 16QAM, and it took 2.647 seconds to transmit.

2.2.5 Summary of the contributions in 5G-SDR open testbeds

The testbed results provide strong evidence of the possibilities of MIMO technology and serve as a solid foundation for the development of a large-scale Massive MIMO testbed.

2.3 Contributions on enhanced carrier aggregation to support 5G use cases

2.3.1 Introduction

This section addresses not only the theoretical impact of Carrier Aggregation (CA) technology but also real network configurations, implementations, and techniques that

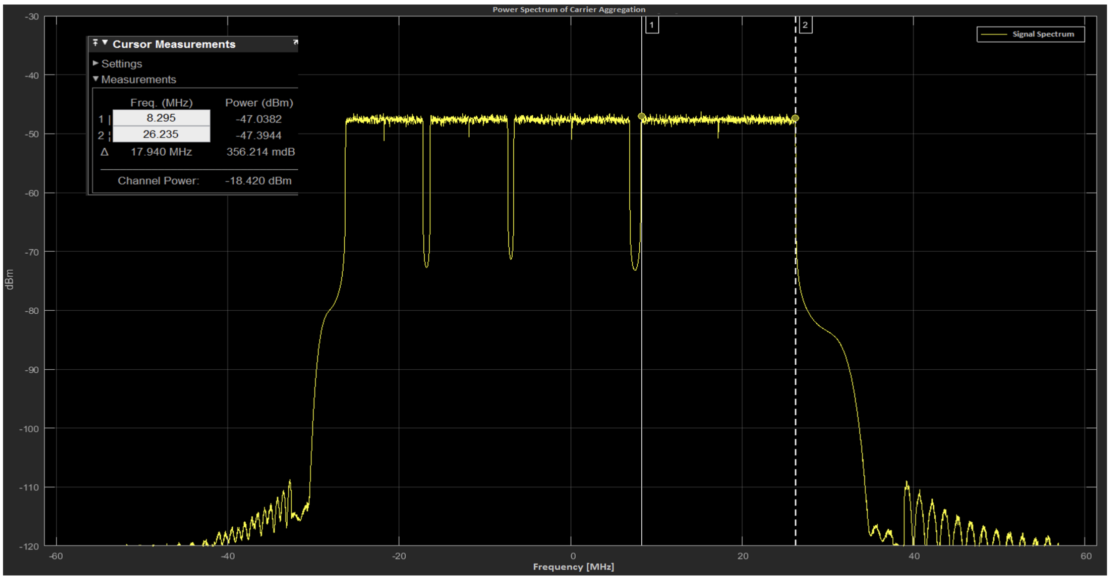

Figure 2.16 Power spectrum of carrier aggregation [13]

support the upcoming high throughput 5G use cases. A performance improvement approach using collected real data is developed to bridge the gap between theoretical Quality of Experience (QoE) expectations and real-world outcomes. According to the captured data, the developed real-life extended band LTE-CA approach enables user throughput rates that approach the theoretical limits.

CA is esential [11] in 5G networks. Using CA, mobile operators can gain access to a 100 MHz frequency bandwidth, aggregating a number of maximum 5 carriers. Mobile operators can achieve high data transfer speeds without needing to own continuous frequency band allocations. They can accomplish this by utilizing statistical multiplexing, which involves dynamically allocating traffic across different carriers.

2.3.2 Carrier aggregation configuration

The diverse range of CA combinations provides ample flexibility for optimizing spectrum utilization and gradually repurposing frequencies previous generations. An illustration revealed in Figure 2.16, depicting the power spectrum of 4 combined carriers developed using the LTE System ToolBox, which is accessible in Matlab. Within 3GPP, the upper limit for channel bandwidth is set at 20 MHz for both Long-Term Evolution (LTE) and LTE-Advanced. Intra-band carrier aggregation (CA) is employed to augment the total capacity across the coverage area. The intra-band version might be either contiguous, non-contiguous, or a combination of both [12].

Intra-Band carrier aggregation

Equation 2.2 defines the spacing between intra-band carriers that were aggregated and positioned adjacently. The channel bandwidth is denoted as Chbw and the nominal spacing is denoted as NS [14].

$$NS = \frac{(\text{Ch1bw} + \text{Ch2bw} - 0.1 \cdot |\text{Ch1bw} - \text{Ch2bw}|)}{0.6} \cdot 0.3\,[\text{MHz}] \tag{2.2}$$

To preserve the orthogonality of the 15 kHz OFDM tones, the spacing must be the least common multiple of 15 and 100 kHz. Thus, the 300 kHz gap is achieved.

2.3.3 Benefits and performances of carrier aggregation technology

CA is an efficient tool that combines the fragmented spectrum owned by operators and offers higher transfer rates.

Downlink throughput calculation for a single carrier

Resource blocks depicts the correspondence between physical channels and resource elements. A physical resource block (PRB) is comprises a number of consecutive OFDM symbols in the time domain and the number of consecutive subcarriers in the frequency domain [15]. The resource element (RE) is the lowest unit of resource available in LTE. A RE contains a subcarrier, during one OFDM or SC-FDM symbol. The spacing between subcarriers is 15 kHz for LTE. The time slot represents a time period of 0.5 ms for LTE frame which corresponds to 7 ODFM symbols and 7 cyclic prefixes (CP) of 5 μs each. A resource block is made of 12 subcarriers, considering a time slot of 0.5 ms. A resource block is composed of 12 subcarriers x 7 symbols = 84 resource elements. In addition, a resource block has 12 OFDM subcarriers, thus the bandwidth is 12 x 15 kHz = 180 kHz. The LTE subframe or time transmission interval (TTI) has 2 slots, 2 x 0.5 ms = 1 ms. Therefore, the LTE frame represents 10 ms or 10 subframes or 20 time slots.

When information data throughput is calculated, the guard band represents 10% of the total bandwidth. The number of subcarriers will be 18 MHz / 15 kHz = 1200. The number of resource blocks will be 18 MHz / 180 kHz = 100. For every informational system, the throughput is calculated as number of symbols per second. Then it is converted to bits per second according to the number of bits that one symbol can carry [16].

In LTE for a 20 MHz channel, 100 resource blocks are available, each block has 12 x 7 x 2 = 168 symbols per ms which means 16.8 Msps. If the used modulation order is 64QAM, then the throughput will be 16.8 x 6 = 100.8 Mbps for one data chain [17]. If the LTE system is implemented with 2x2 MIMO technology, the throughput will double, 201.6 Mbps. Many studies show that 25% of throughput is used for control and signaling. Therefore, a theoretical net throughput of 151.2 Mbps is obtained for downlink. Also, for a 10 MHz channel a 75.6 Mbps throughput is achieved. The respective provided throughput values are processed without considering the employed Forward Error Correction (FEC) code, vendor specific and operator confidential.

2.3.4 Experimental scenario based on field tests

To assess the performance of a real network that has implemented CA technology, a number of field tests in mobility were carried out.

Carrier Aggregation demonstration for 2 inter-band carriers

The tests were conducted using a professional tool, SwissQual QualiPoc Freerider III, equipped with a Samsung Galaxy Note 4 mobile terminal and the post-processing work was performed with Rohde&Schwarz software suite. This mobile terminal supports most LTE bands and it is a category 6, therefore, it can achieve transfer rates of 300 Mbps on DL and 50 Mbps on UL. In these tests, two inter-band FDD carriers were discovered. For this analysis, the lower frequency carrier had a 10 MHz bandwidth and the higher one had a 20 MHz bandwidth with 2x2 MIMO. The mobile terminal has been configured to perform HTTP traffic transfer.

- PDSCH Channel (PDSCH) – the LTE downlink physical channel
- Primary Carrier Component (PCC)
- Secondary Carrier Component (SCC(i))

In order to achieve the use case target, two different HTTP transfer (HTTP) tests were run. The duration of each test was 10 s per session. It is assumed by the telecommunications industry that the maximum transfer peak rate in a 10 s test is the right time value to reflect the network capabilities and to react at requests at maximum performance in the shortest possible time. In the first test, the device was set to access ETSI Kepler Reference Web Page with a size of 800 KB. The mobile terminal succeeded with a 75 Mbps transfer rate.

The aggregated throughput value was around 75 Mbps. Because the file size was too small, it was downloaded before maximum possible transfer rate has been reached.

Signal to Interference Noise Ratio (SINR) level was presented in Figure 2.17 for both PCC and SCC aggregated carriers and both Rx[0] (turquoise line) and Rx[1] (orange line) mobile receiving antennas. For PCC, Rx[0], SINR of 25.94 dB was obtained, and respectively, for Rx[1], SINR of 25.29 dB. For SCC, Rx[0], SINR of 22.83 dB, and for Rx[1], SINR of 21.13 dB were achieved.

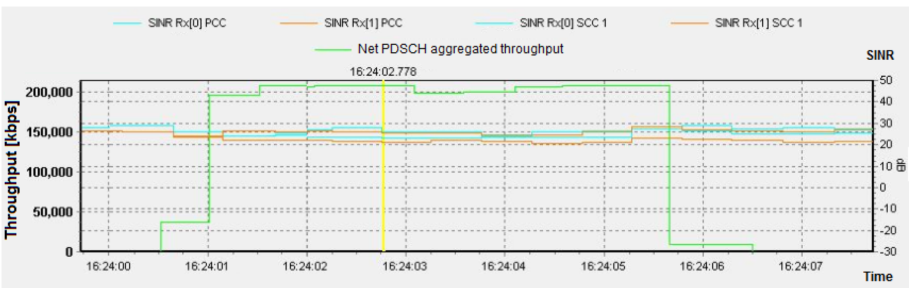

Figure 2.17 SINR for PCC and SCC for a receiver with 2 built-in antennas [13]

The resulted SINR values show very good radio conditions, optimal for a quality 2x2 MIMO eNodeB – user communication. If the SINR values would be too low, this would be a good indicator for coverage optimization. At the same time, highest order modulation would not be selected in case of poor SINR.

2.3.5 Summary of the contributions on enhanced aggregation

Following the captured field tests, the proposed real live extended band LTE-CA approach enables user throughput rates closer to theoretical limits. The PDSCH aggregated throughput followed the scheduled throughput trend.

2.4 Contributions to 5G networks with V2X slices distribution: from concept to deployment and performance evaluation

2.4.1 Introduction

This section introduces a system for allocating network resources, focusing on the distribution of slices while considering the concurrent presence of V2X communications alongside various other types of traffic. The framework is implemented in Python, and its performance is evaluated using real network deployment datasets from a 5G operator. The study extensively simulates the impact of network slicing on several performance metrics, including data rates for V2X, blocking probability, and handover ratio, examining these effects across different combinations of traffic types.

Additionally, this section emphasizes the importance of proper resource allocation to balance V2X and other service types, considering the network traffic load in a given area and ensuring the quality of service for end users.

2.4.2 Related work

This section summarizes the related work which is split into two categories: architectures with various requirements, and network slicing based vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) solutions.

2.4.3 Network slicing architectural overview

This section outlines a comprehensive network slicing framework.

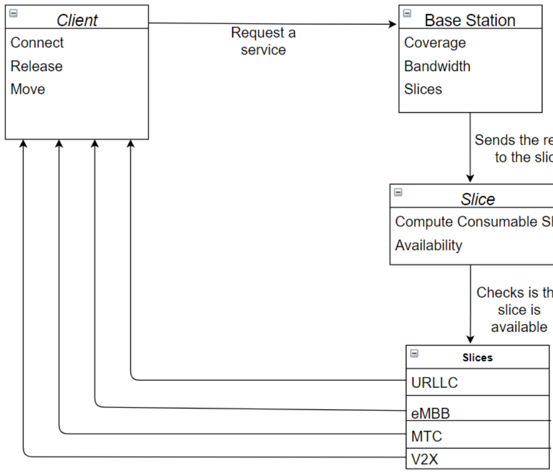

Figure 2.19 Overview of the proposed network slicing framework [18]

Network slicing architecture

Enabled by the integration of SDN and NFV, network slicing is facilitated on a partially shared infrastructure. The common infrastructure contains two types of hardware, one being the dedicated hardware for radio access networks (RANs) and the other being the generic shared hardware for NFV infrastructure resources. The network functions that work on shared hardware are customized based on the requirements of each slice but they cannot be applied in cases where dedicated hardware is compulsory.

2.4.4 Proposed network slicing framework

In this section, first, an outline of the proposed network slicing framework is given and then the detailed algorithms for the three slicing instances defined in the proposed framework are presented.

Framework overview

In Figure 2.19, a sketch of the proposed network slicing framework for V2X applications is presented, considering the co-existence of eMBB, mMTC, and URLLC traffic.

Within this framework, there are defined components or network slicing instances as outlined below. The three slice instances need to inter-operate and communicate with each other as shown in this figure.

- *Client:* A Client instance that needs to be installed in each vehicle.
- *Base Station:* The Base Station instance is responsible for receiving requests from clients and forwarding them to the Slice Management instance.

Algorithm 1 Connect function [18]

```
Input: Slice
Output: Connected clients in coverage
if Client is connected then
    Return;
end if
Connect attempt ++;
if Slice is available then
    Connected users ++;
    Connected ← True;
    return True;
else
    Assign closest basestation;
    if Basestation exists and slice is available then
        Handover count ++;
        if Base station exists and slice is not available then
            Block count ++;
        else
            print 'Client is not in coverage'
        end if
    end if
end if
```

- *Slices* or *Slice Management:* The Slice instance checks the availability of radio resources and allocates accordingly resources to each slice.

Algorithms for the three slice instances

In this subsection, one presents in details the algorithms that need to be performed for each slice instance.

Client

The Client instance is the one that represents end users in a network (UEs, devices, vehicles, etc). There are four steps that a client needs to make in each cycle of a connection session: Lock, Stats, Release, Move.

Locking represents the moment that a client connects to the closest base station and starts to consume or disconnects from it if is already connected. The pseudocode shown in Algorithm 1 describes the connect function in the locking step and counts the number of connected users to a base station. The handover counter increases when a handover is made and the blocking counter increases when a request is blocked (when no sufficient resource available in the slice).

After that, the client has to release the resources it occupied before it disconnects in order for the next client(s) to have available resources as shown in Algorithm 2.

After resources are released, the client can be disconnected from the base station. The algorithm for this step is shown in Algorithm 3.

Algorithm 2 Release consume function [18]

Input: Client
Output: Release_consume()

if *Client* is *connected* and *last usage* > 0 **then**
    Release _ consume();
    if *remaining usage* $<= 0$ **then**
        disconnect;
    end if
end if

Algorithm 3 [18]

Input: Client is connected
Output: Disconnected client

if $connected == False$ **then**
    print 'Client is already disconnected from this slice';
else
    get slice;
    $connected\ users \leftarrow connected\ users - 1$;
    $Connected \leftarrow False$;
    print 'Client connected to this slice';
    return *not connected*;
end if

Algorithm 4 Movement of the client [18]

Input: Initial position of the client (x,y)
Output: Final position of the client

x, y *take the mobility pattern and generate movement*;
$x \leftarrow x + x$;
$y \leftarrow y + y$;
if *Base station exists* **then**
    if *client is not in coverage* **then**
        disconnect;
        assign closest base station;
    end if
else
    assign closest base station;
end if

The last step of a connection cycle is the movement of the client and this procedure is presented in Algorithm 4. After establishing a connection with a base station and consuming the resources allocated to each requested slice, the clients will be disconnected and they may change their positions in space to make a new connection.

To identify the placement of clients and base stations in a region of interest, coordinates are needed. While base stations deployed on fixed locations, and the position of each client is random and may change due to mobility.

Mobility pattern represents the random distribution of client locations. Various mobility models and UE distributions may apply in real-life networks. However, to study

Algorithm 5 Slice management class [18]

Input: name, ratio, connected users, client weight, delay, QoS class, guaranteed bandwidth, maximum bandwidth, initial capacity;

Output: Selected slice

```
Define the used parameters: name, ratio, connected users, client weight, delay, QoS class,
    guaranteed bandwidth, maximum bandwidth, initial capacity;
def function get_consumable_share:
if connected users == 0 then
    return min(initial capacity, maximum bandwidth;
else
    return min(initial capacity / connected users, maximum bandwidth);
end if
def function is_available:
real capacity ← min(initial capacity, maximum bandwidth);
next bandwidth for use ← real capacity/(connected users + 1);
actual QoS of slice = floor(delay * client weight);
if next bandwidth for use < guaranteed bandwidth and
    actual QoS of slice < QoS class then
    return True;
else
    return False;
end if
```

mobility model or client position distribution is beyond the scope of this section. Once the coordinates (x,y) of the current position of a client is known, one is able to check whether it is within the coverage of a base station. If yes, the closest base station to that client is assigned and the checking for the requested slice could begin.

Slice management

Algorithm 5 outlines the pseudocode for slice management including determining the QoS class and the corresponding functions. The function that computes the consumable share of each slice is *get_consumable_share* and it obtains the minimum value between the initial capacity of the slice (which is calculated according to the ratio for each slice) and the maximum amount of resources allocated to each slice. This step is done when no client is connected. When clients start to connect, the initial capacity decreases accordingly, since the total capacity is divided by the number of connected clients. The next function is to check whether the requested slice is available and this step is doing with respect to cell capacity and QoS requirements.

2.4.5 Implementation and network configurations

In this section, an outline on the implementation of the algorithms presented in Sec. 2.4.4 is given and then the network configurations of the proposed simulation based performance assessment are detailed. As a case study, the network scenarios are built based on real-life base station deployment by a network operator in the city of Bucharest.

Implementation outline

Furthermore, the QoS parameters needed in Algorithm 5 are affected by the delay of every service that slices are delivering and are not depending only on the allocated or available capacity for every slice. When delay becomes significant, the achieved QoS will be poor and vice versa. The QoS levels defined in this algorithm have 5 values, with 5 being the poorest service and 1 representing the best one. For delay tolerance, 10 levels are considered where 10 means most delay tolerant and 1 stands for most delay sensitive.

Scenarios and network configurations

For performance assessment, one identified a few use case scenarios based on the real-lift positions of 11 base stations deployed in an area nearby the campus of the University Politehnica of Bucharest, as presented in Figure 2.20.

Figure 2.20 The precise locations of 11 base stations covering a specific region of interest in the city of Bucharest [18].

This region has been selected as an area of interest because there is a big flow of clients and vehicles and it is also a big commercial zone in the city. In this figure, the gNBs are represented by the green circles and for each one of them the position is represented according to the real placement and its coverage is approximated with a circle for the sake of simplicity. The gNBs have the coordinates in the center of the circle (marked by the green circles) with different coverage ranges (as shown in Figure 2.21).

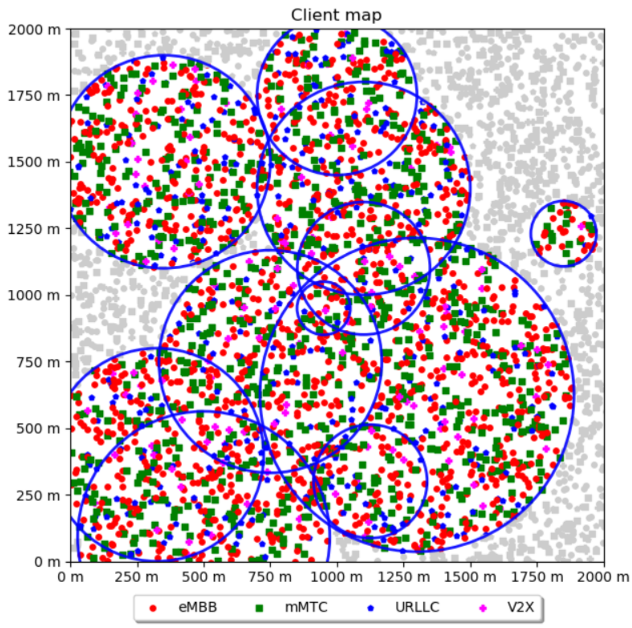

Figure 2.21 Client distribution map for 4000 [18].

The cell capacity at each cell (in Gbps) is partitioned into four slices, each dedicated to one type of applications, i.e., eMBB, URLLC, mMTC, or V2X. The slice resource allocations for the four slices across 11 gNBs are illustrated in Table 2.3.

Table 2.3 Slice distributions across four slices at 11 base stations [18]

BS ID	BS capacity	eMBB[%]	URLLC[%]	mMTC[%]	V2X[%]
922501	25 Gbps	48	30	20	2
910661	30 Gbps	0.3	0.3	0.3	0.1
945911	30 Gbps	20	30	10	40
927241	25 Gbps	45	2	15	38
933301	20 Gbps	45	50	3	2
938721	20 Gbps	14	5	45	36
937121	40 Gbps	28	50	20	2
934101	30 Gbps	47.9	32	2	0.1
933791	30 Gbps	40	30	25	5
934701	20 Gbps	20	55	10	15
927941	35 Gbps	50	5	25	20

This slice distribution is represented by a pre-configured ratio in the configuration file and it dictates how much percent of the total capacity of each cell is allocated to every slice. Note that this ratio is re-configurable.

Table 2.5 Flow specifications w.r.t. QoS and data rate requirements

Slice	Delay tolerance	QoS	Guaranteed capacity	Max. capacity
eMBB	2	5	100 Mbps	1Gbps
mMTC	10	2	1 Mbps	10 Mbps
URLLC	1	2	5 Mbps	50 Mbps
V2X	1	1	5 Mbps	100 Mbps

To investigate the performance of the proposed framework under heterogeneous traffic classes, one introduces a configurable parameter referred to as *weight*, denoted by α, which dictates the distribution of clients across four categories of services. Note that the sum of all the weights must be 1. As an example, the weights for one of the

Table 2.6 Client weights for each slice [18]

Slice	Client weight
V2X	$\alpha = 0.05$
URLLC	$\alpha = 0.13$
mMTC	$\alpha = 0.32$
eMBB	$\alpha = 0.50$

simulations are illustrated in Table 2.6 showing that among all clients 5% of them belong to V2X users, etc. For other simulations, these weights are reconfigured to different values in order to explore the impact of the V2X slice on network performance.

2.4.6 Simulations and numerical results

This section presents the obtained simulation results based on the network configurations explained in Section 2.4.5. For each simulation run, the service requests happened within a duration of one hour were emulated and the reported results in this section are the average values obtained from multiple simulation runs and are averaged over the values obtained across all the 11 BSs. Initially, one sets the value of α to be 0.05 and proceed to analyze the performance based on the five criteria outlined below. Next, in the following two subsections, one analyzes the performance for each client group by modifying the client weight α as the fraction of clients in need of V2X services increases, with respect to the last three criteria.

- Average coverage ratio: Defined as the area that is covered by the base stations with respect to the entire area of the interest.
- Average connection ratio: Defined as the number of clients that are successfully connected divided by the total number of clients in the network.
- Average occupied resources: Defined as the total amount of network capacity (in Gbps) used throughout the whole duration.
- Average handover ratio: Defined as the percentage of ongoing connections that have to perform handover.
- Average blocking ratio: Defined as the percentage of connection requests that have been blocked due to lack of resources.

Overall performance: 2000 versus 4000 clients

When there are 2000 or 4000 clients distributed in the area of interest, the network performance in terms of the five defined metrics is illustrated in Table 2.7.

As expected, more resources are occupied when the number of clients is larger. While 36% of the clients are connected in the 4000-client case, the successful connection ratio for the 2000-client case is only 42%. These values seem to be a low in both cases, but

Table 2.7 Connectivity behavior: 2000 versus 4000 clients [18]

Number of clients	2000	4000
Average coverage ratio	0.54	0.50
Average connection ratio	0.42	0.36
Average occupied resource (Gbps)	22.578	23.931
Average blocking ratio	0.1980	0.2201
Average handover ratio	0.0125	0.0077

the reason behind this behavior is that a large number of clients being located outside the coverage of any base station (the average coverage ratio being 54% for the 2000-client case and 50% for the 4000-client case). In both cases, there are not sufficient radio resources to connect more clients.

2.4.7 Summary of the contributions on V2X network slicing

The impact of network slicing on network performance for V2X services was examined throughout this section.. Specifically, it investigates the effects of integrating the V2X slice with three additional slices (eMBB, URLLC, and mMTC) within a network that includes several base stations. A network slicing architecture that comprises a collection of algorithms required by both clients and base stations was introduced. Extensive simulations were led to evaluate the performance of network slicing, based on a real-life network topology. The investigation considers different network configurations and client distributions across several service categories.

2.5 Considerations beyond 5G

The future evolution of 5G networks (B5G: Beyond 5G) is expected to transition around 2030 to 6G technology. The reason is that 5G will then have reached its limits. For example, certain devices, such as VR (Virtual Reality), require a data rate of at least 10 Gbps, which exceeds the capabilities of 5G [19].

Chapter 3

Search and Rescue meets 5G and UAV to improve missions

This chapter presents the contributions in the Search and Rescue (SAR) field, with a special emphasis on the 5G-based SAR system architecture developed throughout the doctoral studies.[1]

3.1 Search and Rescue: context and background

3.1.1 Salvamont Romania

Salvamont Romania operates through a network of 43 regional and local rescue services spread across the country's various mountain ranges. These teams are typically composed of 1100 professional rescuers and volunteers who are trained in first aid, climbing, skiing, and other relevant skills. Salvamont often works in coordination with other emergency services, such as the police, military, and medical teams, especially during large-scale rescue operations or natural disasters.

3.1.2 Romanian landscape

Romania is home to more than 12.000 caves [20], many of which are located in or near mountainous regions. Caving, or spelunking, is a popular but risky activity that can lead to accidents, including getting lost, trapped, or injured. The sheer number of caves adds to the complexity and scope of the rescue operations that Salvamont must be prepared to handle.

[1] Disclaimer: This work material is produced and described to present an initiative designed to support life-saving intervention teams and is not intended to promote economic agents, companies or advertise products whose logos may appear in the images, and which could not be removed or neutralized. The results were obtained during the research carried out, having impact in real-life scenarios for saving human lives.

3.1.3 The challenge and the need

The rugged terrain of the Carpathian Mountains, abundant in deep gorges and steep rocky walls, makes it almost impossible for people to get cellular mobile coverage all over the mountain and call for help. The difficult terrain also makes it extremely difficult for search and rescue teams to locate the victims. Every year, Salvamont, takes part in over 7200 rescue operations [21].

In 2023, Salvamont rescuers have been dispatched to take action in 6.548 rescue operations and Cardiopulmonary Resuscitation (CPR), interventions in which 8.026 people were saved. Among them 4272 actions took place in the winter season, most of them related to winter sports while 2221 actions took place in the summer season. A number of 110 actions were done in hard-to-reach locations, outside of the mountain area in which the intervention of the rescuers was solicited [22].

3.2 Proposed solution

3.2.1 Towards the technological response

The research in this section is fully available in the submitted thesis and, due to intellectual rights and intention to disseminate it in a journal article in maximum 24 months, it is not made available in this abstract which will be uploaded on the Internet. Thus, the tools will automatically report false-positive similarities.

3.2.2 The benefits

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3.2.3 Proposed 5G-based SAR system architecture

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3.2.4 Description of the SAR system operation

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3.2.5 SARUAV software solution integration

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3.3 Experimental results obtained during the 5G measurement campaign in SAR scenarios

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3.3.1 Scenario 1: Mountain rescue – rural, remote areas - “Vârful lui Roman” peak

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3.3.2 Scenario 2: Urban – public safety, disaster recovery, tactical bubble

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Chapter 4

Drones impact in eight industries

4.1 5G enabled drones highways

Mobile network data can be used in helping the drones fly whether that is aiding routine access in hard-to-reach areas, delivering lifesaving supplies to hospitals, or acting as first responders in accidents and helping emergency crews to arrive prepared. Through network APIs, explained earlier, flight path manager platforms enables manual and autonomous operations through customized 5G network slices, creating drones' virtual highways or drones' corridors.

The proposed solution is an integrated platform for remote UAV operations and mission planning (Figure 4.1), which lowers the entry cost and complexity barriers for multi-type missions and business service providers, democratizing the access to the drone business. It is a vendor agnostic OpenAPI platform, 5G enabled, that can be easily used

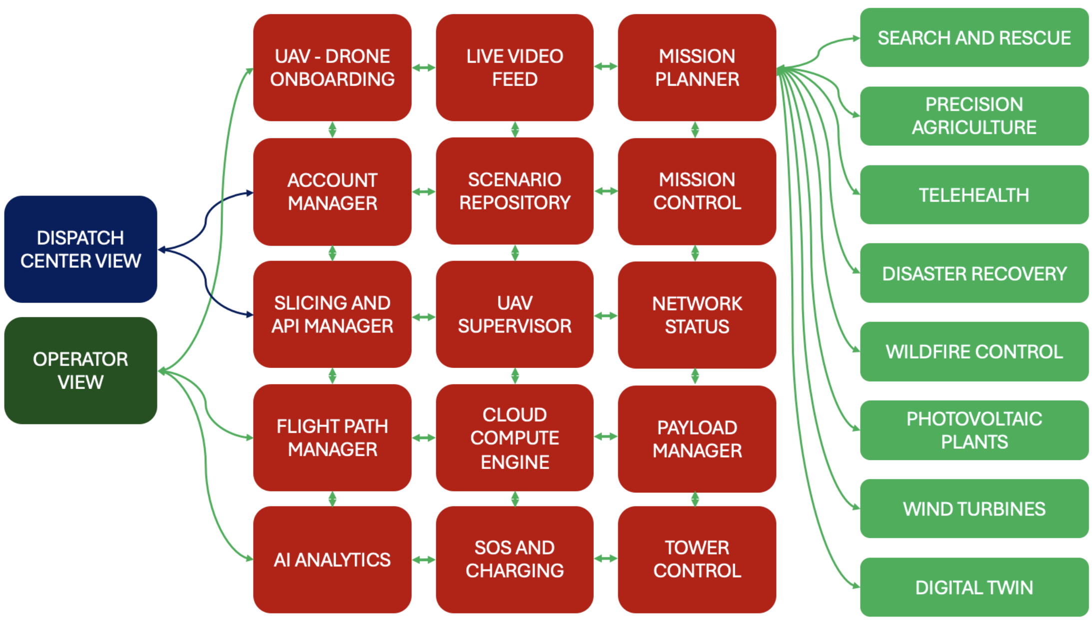

Figure 4.1 Developed platform for UAV operations

for processing various data types from different sources leveraging the most powerful

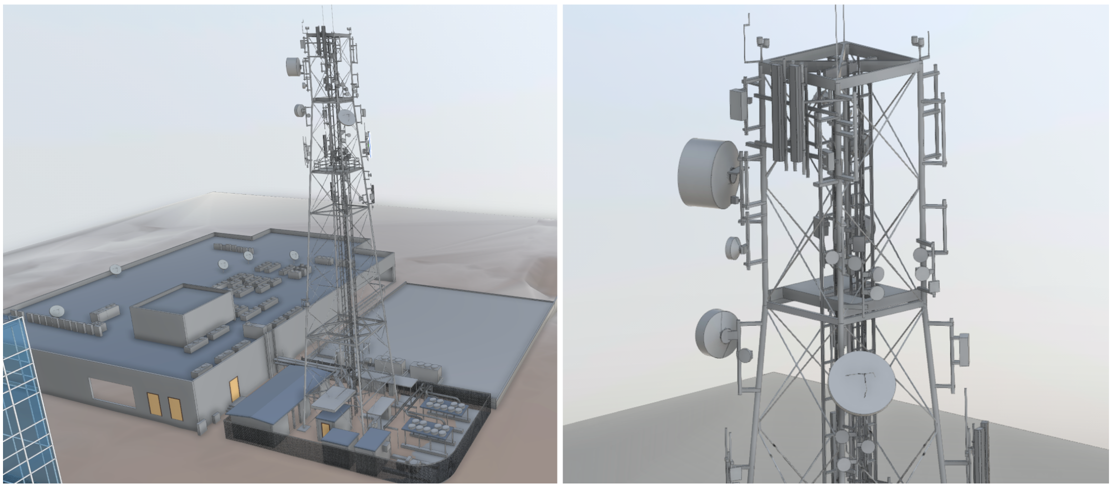

Figure 4.2 Personally captured photograms processed with MYX Robotics platform [23]

cloud AI/ML engines available in real-time. The platform flight path manager enables manual and autonomous operations through customized 5G network slices, creating drone virtual highways. Secure Guard module guarantees flight parameters for mission safety and compliance as well as the detection and prevention of illegal behavior. The system has real-time civil aviation oversight and can automatically generate and send legal forms for official mission approval. It allows the onboarding of custom commercial and industrial drones and the setup with any mission specific accessories.

Among the first projects which involved the use of drones was purposed to create the digital twin of Vodafone's network infrastructure (Figure 4.2), with the aim of reducing the time spent on inspection, scanning, design, and maintenance, having a direct impact on the safety and security of the engineers.

4.2 Sustainable energy production based on 5G communications and UAV inspection

4.2.1 UAVs in energy production

In the context of monitoring and maintaining the efficiency of a photovoltaic (PV) farm, it is important to recognize that the elements of solar panels can deteriorate gradually over time. This degradation occurs incrementally, leading to a gradual decrease in power output, which can have significant financial implications over extended periods. To determine whether there has been a drop in power production at the PV farm under study, a thermal inspection of the panels was conducted using a drone.

Regular inspections of solar panels are often undervalued, with the common belief being that any issues would be noticeable through a drop in energy production. However, this approach is not effective for identifying defects because daily fluctuations in weather-related factors such as temperature, humidity, cloud cover, sunlight, and radiation angle make it difficult to make accurate comparisons. While major issues like inverter shutdowns can be detected depending on the size of the solar park and the monitoring system in place, even then, pinpointing the exact location of the affected panels and inverters can be challenging.

4.2.2 Center for Research and Advanced Technologies for Alternative Energy Photovoltaic Farm

The Center for Research and Advanced Technologies for Alternative Energy (CETATEA) was established as part of the broader transition toward renewable energy.

4.2.3 PV panels anomalies detection

To determine whether there was any reduction in power output from the PV farm, a thermal inspection of the panels was conducted using a drone. This method is highly reliable and precise, utilizing state-of-the-art equipment to ensure the highest quality data.

An industrial-grade drone (specifically, the DJI M300 RTK) equipped with a thermal imaging camera (Zenmuse H20N sensor with a resolution of 640×512 pixels for thermal images) was employed. This setup allows for the generation of automatic reports that pinpoint anomalies and provide precise data for comparison. The temperature range of the sensor spans from -20°C to 150°C in High Gain mode and from 0°C to 500°C in Low Gain mode, with a spectral band of 8-14 μm and a sensitivity (NETD) of $\leq$ 50 mK at an aperture of f/1.0.

Three types of anomalies were inspected: (1) solar cell defects, (2) diode issues, and (3) inverter malfunctions. The initial step involved examining the PV panels for hot spots or solar cell defects, which are the most common issues (Figure 4.3). Shading on a module or a faulty cell can cause the module to switch from producing power to consuming it, leading to heating of the cell, which appears as a hot spot in thermal images. Defective cells exhibit higher electrical resistance, converting power into heat.

The recorded temperatures of the affected solar cells range from 55.6°C (SP2) to 79.3°C (SP3), as detailed in Table 4.1.

For a functioning PV panel, thermal scanning shows a minimum operating temperature of 58.6°C and a maximum of 60.9°C (Figure 4.5). The higher temperatures listed in Table 2 (e.g., 79.3°C for SP3, 63.2°C for SP5, and 68.5°C for SP7) confirm the presence of hot spots on the three faulty panels, affecting a total of eight cells.

An example of a healthy panel, the maximum temperature is 60.9°C, and the minimum is 58.6°C, which concludes an average of 59.8°C, which is a normal working temperature, and no abnormal hot spots were detected.

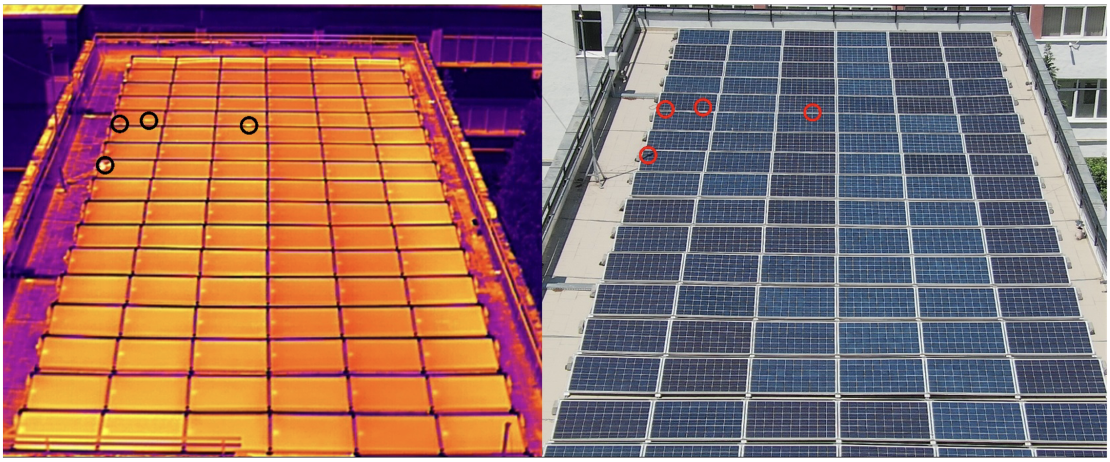

Figure 4.3 Thermal scanning using drone inspection displays the hot spots on the PV farm [24]

Table 4.1 Temperature measurements at different points of the PV systems [24].

Spot	Measured temperature
SP1	62.0° C
SP2	55.6° C
SP3	79.3° C
SP4	61.1° C
SP5	63.2° C
SP6	58.4° C
SP7	68.5° C
SP8	59.3° C

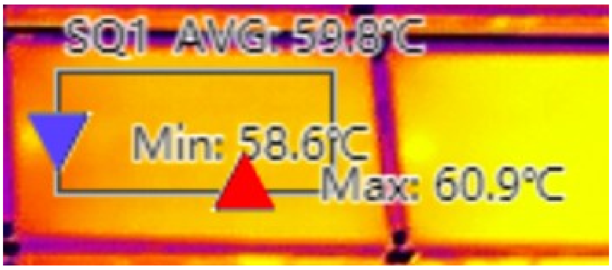

Figure 4.5 Temperature values on a healthy panel

4.2.4 Conclusions

Thermal drone inspections are highly effective for identifying these types of defects and are considered among the most efficient methods for evaluating photovoltaic plants. This technology is invaluable not only during the design phase—where it helps create orthophoto mosaic plans, compute shadow indices, and optimize panel orientation—but also during the commissioning phase to ensure everything functions as expected. Furthermore, regular inspections during the operational phase, especially before the panel warranty expires, can help identify and replace faulty panels without incurring additional costs.

In conclusion, the thermal inspection suggests that the power production of the PV panels at CETATEA is efficient and aligns with the estimated output.

Chapter 5

Innovative 5G Open network developed in R&D Innovation Hub

5.1 Open 5G and UAVs meet Vodafone Innovation Hub: mission and objectives

The Vodafone Innovation Hub (Figure 5.1) is a significant project that I have led during my research time with the purpose of leaving a legacy behind for new generation to come. Located in the National University of Science and Technology Politehnica Bucharest (UPB), Faculty of Electronics, Telecommunications and Information Technology, the hub was established through the active involvement and substantial contributions of the author of this thesis. This project, initiated by the author of this thesis and Vodafone Romania as the university's pioneering center of excellence, functions as a multidisciplinary hub focused on education, research, and entrepreneurial support. It unites various academic disciplines within electronics, telecommunications, and information technology, fostering an innovative atmosphere that bridges the gap between academia and industry requirements.

5.2 Open 5G base station deployment

5.2.1 5G network architecture

The research in this section is fully available in the submitted thesis and, due to intellectual rights and intention to disseminate it in a journal article in maximum 24 months, it is not made available in this abstract which will be uploaded on the Internet. Thus, the tools will automatically report false-positive similarities.

Figure 5.1 Vodafone Innovation Hub: before and after

5.2.2 OpenRAN system architecture

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5.2.3 5G in a Box high level architecture

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5.2.4 5G in a Box physical prototype

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5.2.5 5G in a Box test scenarios and measurements

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5.2.6 Evaluation of air interface for the functional 5G in a Box

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Chapter 6

Conclusions

6.1 Obtained results

The thesis emphasizes the study of heterogeneous technologies that contribute as Tech for Good triggers and social impact enablers: mobile radio coverage in remote areas, 5G mobile networks key enablers such as MIMO technology as foundation for Massive-MIMO, carriers aggregation for wider bandwidth and increased data, different modulation schemes and detection algorithms, the breakthrough 5G network slicing feature enabled by 5G Standalone core that will dramatically change the industrial sector's capabilities, open 5G networks, open RAN, open Core, network virtualization, custom-made drones, 4G/5G cells on drones and 5G in a Box to prove innovative and compact implementations. In addition, it highlights a large panoply of experimental results that validates their interoperability and performance.

For example, in Chapter 2, the most innovative findings of my study focus on the advent of 5G, which I identified as a transformative technology capable of enabling a wide array of advanced applications. By implementing new technologies like MIMO, OFDM, and network slicing, and aggregated frequency bands, 5G not only achieves enhanced mobile broadband but also supports ultra-reliable low-latency communications and massive machine-type communications. My research also anticipates the ongoing development towards 6G, which promises to further elevate network capabilities.

Furthermore, the work on enhanced Carrier Aggregation (CA) highlights its essential role in boosting data transfer rates and enhancing overall network performance, particularly within the 5G framework. Through extensive field testing and practical evaluations, I developed a real-world approach that brings user throughput rates closer to theoretical maxima, underscoring the significance of CA for both current LTE and future 5G networks. This research underscores the need to optimize radio frequency and coverage conditions to prove the benefits of CA technology (e.g. improving SINR). It also supports the transition to 5G by incorporating multi-carrier aggregation, advanced modulation schemes as 256QAM, and massive MIMO. The findings provide mobile operators with valuable insights into leveraging fragmented spectrum and selecting optimal frequency carriers to enhance network performance, ultimately demonstrating that CA is a crucial feature for both existing and next-generation mobile networks.

Finally, Chapter 2 studies the impact of network slicing on V2X services by analyzing the integration of a V2X slice with other slices, such as eMBB, URLLC, and mMTC, within a network comprising multiple base stations. A network slicing architecture, along with algorithms for both clients and base stations, was developed and rigorously tested through extensive simulations based on a real-world network topology. The findings reveal that network performance, related to resource utilization, handover efficiency, and blockage, varies according to the number of clients and their distribution across different service categories. The study underscores the critical importance of equitable resource allocation among slices to ensure optimal performance under diverse network deployment and traffic scenarios.

Chapter 3 revealed that the integration of 5G technology and Unmanned Aerial Vehicles (UAVs) into Search and Rescue (SAR) operations had a significant impact in the way missions are conducted in Romania's challenging mountainous regions. By leveraging a custom-designed UAV system equipped with high-power antennas and artificial intelligence, rescuers can now extend mobile network coverage to remote areas previously unreachable by traditional means. This innovative approach, developed through a collaboration between Salvamont Romania and Vodafone Romania, allows drones to provide mobile coverage up to 10-kilometer cell radius depending on the terrain, ensuring that individuals in distress can connect to emergency services even in the most rugged terrains. Additionally, the drones capture high-resolution images, which are analyzed by SARUAV AI software to detect and locate missing persons quickly. The entire system, including a mobile telecommunications unit housed in a mini-trailer, purposed to be cost-efficient, scalable, and rapidly deployable, a groundbreaking tool in life-saving missions. The nationwide implementation of this technology across 14 data analytics centers has significantly reduced search times, increased the success rate of SAR operations, and set a new standard for rescue efforts in difficult environments, already supporting in rescuing two people alive.

In Chapter 4, the widespread adoption of 5G-enabled drone highways is introduced. It represents a significant step forward in the adoption of UAVs across various industries, transforming how they operate and interact with their environments. Moreover, this chapter explores the profound impact that drones, enhanced by 5G technology, have on eight key sectors, including energy production and telecommunication infrastructure. The innovative integration of drones in these fields has not only streamlined operations but also reduced costs, increased efficiency, and improved safety. For instance, in energy production, particularly within solar farms, drones equipped with thermal imaging cameras can swiftly detect defects in photovoltaic panels, ensuring optimal performance and minimizing financial losses due to unnoticed power degradation. The introduction of drone highways, which rely on advanced 5G network slices, enables these UAVs to operate beyond the visual line of sight, opening up new possibilities for autonomous missions in hard-to-reach areas and enhancing the capabilities of industries that depend on accurate and timely data. As drones become more integrated into these sectors, they are set to enhance the traditional methods, providing a sustainable, efficient, and safer alternative that leverages the latest technological advancements.

Chapter 5 reveals how the Vodafone Innovation Hub at Politehnica Bucharest, led by the thesis author, has significantly advanced the integration of cutting-edge technologies into academic research and education. The hub's infrastructure, including 5G networks, IoT platforms, and UAVs, has enabled the development of innovative projects across various fields, such as smart drones for environmental monitoring. These scientific achievements have not only enhanced the practical and theoretical understanding of emerging technologies among students but also fostered interdisciplinary collaboration, resulting in tangible solutions that bridge academia and industry.

In addition, the Chapter 5 presents ”5G in a box” solution developed throughout this thesis based on technological assets in Vodafone Innovation Hub, with all the scenarios and experiments proposed and performed to assess the key performance of Open RAN and 5G networks. The "5G in a Box" project exemplifies an innovative approach to deploying a complete 5G Standalone (SA) network within a compact, portable form factor, utilizing open-source software and commercially available hardware. By integrating the srsRAN for the Radio Access Network (RAN) and Open5GS for the core network, the project demonstrates a cost-effective, flexible solution that makes 5G technology more accessible for a wide range of applications, including research, education, and specialized field deployments.

6.2 Original contributions

1. First of all, I proposed an innovative approach for students, future engineers and experts from radio communications domain to understand that starting from theoretical fundamentals, followed by practical testbeds experiments, an idea can become a real life-saving implementation.
2. I brought under the spotlight the real evolution of mobile radio networks proving with experimental results the impact in different domains.
3. I have designed and implemented the first software-defined radio test-bed in POLITEHNICA University to showcase the real technology of MIMO radio systems with spatial-multiplexing before this feature to be present in any commercial network.
4. I managed to create a powerful overview as a guide for undestanding how 5G networks are functioning in real-life networks.

5. I tested different configurations of the MIMO SDR testbed to differentiate the impact of different modulations schemes, channels bandwidth and detection algorithms.
6. I designed and ran a comprehensive measurement campaign to prove the power of critical technology in 5G, called Carrier Aggregation.
7. I deduced a new equation and demonstrated how the mobile data throughput is computed on a mobile phone.
8. I involved various professional equipment in field tests for proving the impact of this technology directly on the end-user experience.
9. I implemented a fully virtualized 5G Network Slicing Orchestrator to demonstrate the evolution of 5G and the impact of this new dedicated resource allocation technology in the next-generation use-cases that require ultra-low latency, strong reliability and massive data transfer.
10. I focused the study and experimental part on systems on mobility as V2X, with a clear purpose to prepare the new paradigm, called drone highways, which are requiring a strong 5G connection for Beyond Visual Line of Sight operations (BVLOS).
11. I proposed a performance evaluation methodology for the network slicing orchestrator to assess the maximum number of user that can be accommodated.
12. I designed an unique system called "The Flying cell", that brings mobile radio coverage with all the technologies, including 5G, in remote mountain areas to support search and rescue missions of Salvamont Romania.
13. I had a strong contribution in imagining the architecture and in creating the first functional prototype that was tested in the field.
14. I proposed the idea to build a drone that can be equipped with a radio frequency antenna.
15. I proposed the data processing solution to be implemented in a very compact way in a mini-trailer.
16. I conducted various measurement campaigns in the mountains with Salvamont teams to adjust the network parameters on their needs.
17. I tested and adapted various antennas configurations and ground equipment to find the best implementation that provides maximum performance in heavy duty scenarios no matter the weather conditions.
18. In order to cover various scenarios in the mountain rescue missions, I contributed in implementing, testing, adjusting and training phases for the SARUAV automatic AI-based clues detection system developed by SARUAV Poland.

19. I supported Salvamont in extending this project with support from Vodafone Romania to 14 counties in Romania.
20. I demonstrated with support from SAR teams that this set of technologies can save human lives, based on the two real cases reported with persons found alive in the Romanian rural area using drones.
21. I contributed to the implementation of the first 4G/5G base station integration through a LEO satellite communication network that connected the drone cell to the core network of Vodafone Romania.
22. I proposed a new scenario involving the drone cell tower for urban public safety, disaster recovery and tactical bubble for the authorities.
23. I conducted tests and trials in difficult scenarios surrounded by buildings, increased population and high density of urban standard macro cell towers.
24. I demonstrated various performance parameters to successfully validate the drone cell tower solution even in urban area.
25. I have proposed a new state-of-the-art software platform for new generations of drones covering eight industries for professional activities.
26. I contributed and operated the practical assessment for an innovative inspection of photovoltaic panels infrastructure in collaboration with INCDTIM Cluj Napoca, proving the impact and utility of drones equipped with thermal vision cameras in preventive maintanance for such assets.
27. I proposed and designed on behalf of Vodafone Romania and Politehnica Bucharest the first multidisciplinary center of excellence in ETTI Faculty called Vodafone Innovation Hub.
28. I contributed to the entire educational, didactic and infrastructure test beds and implemented technologies in the hub to provide access to students to learn and build prototypes, and to have a strong focus on research and development.
29. I generated a custom-made idea concept called 5G in a Box to prove the power of future Open 5G networks and contributed to the implementation of this system in Vodafone Innovation Hub.
30. I contributed to creating a fully open-source implementation for RAN and CORE, providing an innovative differentiator in comparison with other implementations, by running the entire system on a small Raspberry Pi 5 and then decoupling the core part on a powerful server for better overall performance.
31. I proposed and implemented a new drone system based on the 5G in a Box system adapted in order to proof the concept of mission critical 5G tactical bubble. It is worth mentioning that, at the same time, the system can be transformed in a

network quality and parameters scanner to evaluate the radio conditions for the future drones highways.

32. I contributed to the proposal of different scenarios and different configurations to assess the capabilities of 5G in a Box and the strong potential of Open 5G networks for bespoke applications.
33. I have contributed to the handover implementation using two 5G in a Box systems acting as two radio cells for a cognitive network.
34. I left a legacy behind through the amazing educational innovation hub where ideas are becoming reality with support of new technologies and by proposing two innovative solutions that will set the directions in the radio-communications domain.

6.3 List of original publications

Journal articles

[J1] **C. Zamfirescu**, R. Iugulescu, R. Crăciunescu, A. Vulpe, F. Y. Li, and S. Halunga. Network slice allocation for 5G V2X networks: A case study from framework to implementation and performance assessment. *Vehicular Communications*, vol. 45, pp. 100691, February 2024. (**ISI, Q1, IF: 5.8**).

[J2] A.-M Drăgulinescu, **C. Zamfirescu**, S. Halunga, I. Marcu, F. Li, and O. Dobre. Understanding LoRaWAN Transmissions in Harsh Environments: A Measurement-based Campaign through Unmanned Aerial/Surface Vehicles. *IEEE Trans. on Instrum. & Meas.*, vol. 73, pp. 1-14, 2024, Art no. 5501514, 2024. (**ISI, Q1, IF: 5.6**).

[J3] A.-M Drăgulinescu, S. Halunga, and **C. Zamfirescu**. Unmanned vehicles' placement optimisation for Internet of Things and Internet of Unmanned Vehicles. *Sensors*, 21(21), 2021. **(ISI, Q2)**.

[J4] R. Nelega, D.I. Greu, E. Jecan, V. Rednic, **C. Zamfirescu**, and E. Puşchiţă. Prediction of Power Generation of a Photovoltaic Power Plant Based on Neural Networks. *IEEE Access*, vol. 11, pp. 20713-20724, 2023. (**ISI, Q2**).

[J5] F. Turcu, A. Lazar, V. Rednic, G. Roşca, **C. Zamfirescu**, and E. Puşchiţă. Prediction of Electric Power Production and Consumption for the CETATEA Building Using Neural Networks. *Sensors*, 22(16), 2022. (**ISI, Q2**).

Conference articles

[C1] **C. Zamfirescu**, A. Vulpe, S. Halunga, and O. Fratu. Spatial multiplexing MIMO 5G-SDR open testbed implementation. *Lecture Notes of the Institute for Computer*

Sciences, Social-Informatics and Telecommunications Engineering, LNICST, 2019, vol. 283. (**ISI**).

[C2] **C. Zamfirescu**, B. Burchilă, and O. Brădeanu. Enhanced carrier aggregation to support 5G use cases. *Proceedings of SPIE - The International Society for Optical Engineering*, 2018. (**ISI**).

[C3] A.-M. Drăgulinescu, A. Drăgulinescu, **C. Zamfirescu**, S. Halunga, and G. Suciu Jr. Smart Neighbourhood: LoRa-based environmental monitoring and emergency management collaborative IoT platform. In *2019 22nd International Symposium on Wireless Personal Multimedia Communications (WPMC)*, pages 1–6, 2019. (**ISI**).

[C4] C. Mărculescu, A.-M.C Drăgulinescu, A. Machedon, I. Marcu, and **C. Zamfirescu**. LoRa and Bluetooth-based IoT alarm clock device for hearing-impaired people. In *2020 IEEE 26th International Symposium for Design and Technology in Electronic Packaging (SIITME)*, pages 140–143, 2020. (**ISI**).

[C5] A.-M. Drăgulinescu, I. Marcu, and **C. Zamfirescu**. An End-to-End LoRaWAN-based IoT Platform with Built-in Network Coverage Testing Capability. In *2022 25th International Symposium on Wireless Personal Multimedia Communications (WPMC)*, Herning, Denmark, 2022, pp. 474-479. (**ISI**).

[C6] A.-M. Drăgulinescu, **C. Zamfirescu**, and B. Ionescu. Salv AIoT Platform for Mountain Accidents Prevention and Search and Rescue Missions. In *2024 IEEE International Conference on Communications Workshops (ICC Workshops)*, IEEE, pp. 1475–1480, Jun. 09, 2024. doi: 10.1109/iccworkshops59551.2024.10615751.

[C7] E.G. Stănescu, T. C. Stoian, D. I. Năstac and **C. Zamfirescu**, Intelligent System for Integration in 5G Networks, IEEE 30th International Symposium for Design and Technology in Electronic Packages (SIITME), Sibiu, Romania, 16-19 Oct. 2024 (abstract accepted, paper under review).

[C8] **C. Zamfirescu**, A. Drăgulinescu, S. Leonte, B. Ionescu - The impact of 5G and AI in mountain rescue critical missions - to be submitted for review.

[C9] **C. Zamfirescu**, D. Burmaz, R. Iugulescu, B. Ionescu - The future of Open RAN networks - Building a “5G in a Box” network - to be submitted for review.

6.4 List of conferences and lectures

IEDO CONF (IEDO – International Emergency Drone Organization - Paris, France) is the world emergency robotic IEDO conference.

With support from Vodafone Romania, I have participated in tens of conferences, lectures, interventions in society on future technologies topics related to my research work and job’s activity.

This is a selection of various domains I publicly engage with. The primary audience is the Romanian society, which benefits from most of the projects presented.

[L1] New TechForGood premieres with Vodafone and Salvamont Romania. *Business Review*. https://business-review.eu/tech/telecom/new-techforgood-premieres-with-vodafone-and-salvamont-romania-249013.

[L2] Drones and AI for mountain rescue missions in Romania. *Vodafone News*. https://www.vodafone.com/news/technology/drones-ai-mountain-rescue-missions-romania.

[L3] Ciprian Zamfirescu – Evoluția este învățare. *Business Magazin – Top 100 Young Leaders*. https://www.businessmagazin.ro/business-hi-tech/ciprian-zamfirescu-evolutia-este-invatare-21334687.

[L4] 3 mituri despre digitalizare demontate de Ciprian Zamfirescu, Managerul Inovației de la Vodafone. *IQ Digital*. https://iqdigital.ro/2023/07/18/video-3-mituri-despre-digitalizare-demontate-de-ciprian-zamfirescu-managerul-inovatiei-de-la-vodafone/.

[L5] Andi Moisescu Podcast 1. https://www.youtube.com/watch?v=uaVhDs27Lps.

[L6] Andi Moisescu Podcast 2. https://www.youtube.com/watch?v=9kZP5jvs-KY.

[L7] Romania 3.0 Event. *Antena3 CNN*. https://platforma4.mediatrust.ro/browser/tv/TXOJWR/z/t.

[L8] International Mountain Rescue Race. Accessed at https://www.youtube.com/watch?v=YK6NoOiGa5o.

[L9] Ciprian Zamfirescu – IlikeIT. *ProTV*. https://platforma4.mediatrust.ro/browser/tv/8QJLBL/z/t.

[L10] Ciprian Zamfirescu: PNRR ar putea sa transforme statul roman intr-un purtator de inovatie. *Financial Intelligence*. https://financialintelligence.ro/ciprian-zamfirescu-pnrr-ar-putea-sa-transforme-statul-roman-intr-un-purtator-de-inovatie-video/.

[L11] Ciprian Zamfirescu: Digital Transformation Manager, Vodafone Romania. *Ziarul Financiar*. https://m.zf.ro/business-hi-tech/ciprian-zamfirescu-digital-transformation-manager-vodafone-romania-21191828.

[L12] Primul Centru de Excelenta. *B1TV*. https://platforma4.mediatrust.ro/browser/tv/LXN1Y1/z/t.

[L13] Ciprian Zamfirescu on YouTube. Available at: https://www.youtube.com/watch?v=vZkVDW2SOGw&t=61s.

[L14] Financial Intelligence Conference - Forumul Romania Digitala 2022. *Financial Intelligence*. https://www.financialintelligence.ro/forumul-romania-digitala-2022.

[L15] IQ Digital Cluj-Napoca Conference – The demystification of digitalization 2023. *IQ Digital*. https://www.iqdigital.ro/cluj-napoca-conference-2023.

[L16] Conferinta Tigers of Romania – Start-up.ro – The impact of drones in 8 industries 2024. *Start-up.ro*. https://www.start-up.ro/tigers-of-romania-2024.

[L17] Podcast fapte bune – Fundatia Vodafone – Tech for Good - 2023. *Fundatia Vodafone*. https://www.vodafone.com/fundatia-vodafone/podcast-tech-for-good-2023.

[L18] CISA IKAR Conference in Montreux – Drones in Romanian mountain rescue – 2022. *CISA IKAR*. https://www.cisa-ikar.org/conference-montreux-2022.

[L19] Mara Emergency Med Conference – The impact of drones in first response 2023. *Mara Emergency*. https://www.maraemergency.ro/conference-2023.

[L20] Techsylvania Conference – Technology behind Telecommunications. The journey from Telco to TechCo. 2022. *Techsylvania*. https://www.techsylvania.com/conference-2022.

[L21] Podcast Andi Moisescu – Revolution in Education 2023. *Andi Moisescu Podcast*. https://www.andimoisescu.com/podcast-revolution-education-2023.

[L22] Simple with Technology – Professional drones for rescue missions 2023. *Simple with Technology*. https://www.simpletech.ro/professional-drones-rescue-missions-2023.

[L23] ZF High-Tech Innovation Summit – The potential of innovation in Romania 2022. *ZF High-Tech*. https://www.zfhightech.ro/innovation-summit-2022.

[L24] Republica Magazin – The technology that saves lives – 2023. *Republica Magazin*. https://www.republicamagazin.ro/technology-saves-lives-2023.

[L25] RO 3.0 Plans and perspectives for Romania. *RO 3.0*. https://www.ro3.0.ro/plans-perspectives-2023.

[L26] ilikeIT PROTV – The drones technologies in mountain and water rescue. *PROTV ilikeIT*. https://www.protv.ro/ilikeit/drones-technologies-rescue-2023.

6.5 List of national projects

[Pn1] Research Assistant, *Smart viticulture based on IoT techniques – a premise for managing climate change*, ADER 6.3.13 (ID: 320235340), Competition within the Sectoral Plan for Research and Development in the field of Agriculture and Rural Development of the Ministry of Agriculture and Rural Development, for the years 2023-2026, Agriculture and Rural Development - ADER 2026. Principal Investigator: Dr. Ana-Maria Drăgulinescu, 2023-2026.

[Pn2] Research assistant, PN3 type 'Solutions' no. 5Sol/2017, *ToR-SIM Project: Integrated software platform for malware analysis of mobile terminals*, Project Director Prof. Octavian FRATU, 2017-2019.

6.6 List of international projects

[Pi1] Research Assistant, EEA Norway Grants, *SOLID-5G Project: IoT Platform based on Massive MIMO with Network Slicing for IoV/V2X and Maritime Services in Beyond 5G Networks*, Project Manager at UPB: Assoc. Prof. Marius VOCHIN, 2021-2023.

[Pi2] Project Manager (Partner: Vodafone Romania), Connecting Europe Facility - Digital, *5G-ENRICH Project: 5G-Edge Network for Reinventing Innovation in Community and Higher-Education* (current status: Grant Agreement Preparation - GAP).

6.7 Impact of the results

6.7.1 Scientific impact

The contributions made significantly advance the understanding and application of modern radio communications technologies, particularly within the educational and experimental contexts. By proposing an innovative approach that connects theoretical fundamentals with practical testbeds, I have facilitated a deeper understanding for students, future engineers, and experts. The establishment of the first software-defined radio test-bed at Politehnica University, showcasing MIMO radio systems with spatial multiplexing, was pivotal in preempting commercial network developments. Furthermore, the design and implementation of the 5G Network Slicing Orchestrator demonstrated the practical evolution of 5G technology, emphasizing its impact on next-generation use cases requiring ultra-low latency, high throughput, along with a high level of reliability. These contributions have laid the groundwork for ongoing R&D in radio communications.

6.7.2 Innovation-related impact

The innovative efforts outlined have not only pushed the boundaries of existing technologies but also introduced novel concepts and implementations. The "5G in a Box" system, for instance, provided a tangible demonstration of the future potential of Open 5G networks. My design and execution of the first functional prototype of a drone-based mobile radio coverage system, capable of supporting rescue missions in remote mountain areas, exemplifies the intersection of innovation and practical application. Additionally, the proposal and realization of the Vodafone Innovation Hub at POLITEHNICA Bucharest have created a multidisciplinary center of excellence, fostering innovation in education, research, and technology development. These initiatives highlight a strong commitment to pushing technological frontiers and creating new paradigms in the field.

6.7.3 Social impact

The social implications of my work are far-reaching, particularly in enhancing public safety and supporting critical rescue missions. The development of "The Flying Cell" system, which provides mobile radio coverage in remote areas, has been instrumental in supporting search and rescue missions, thereby directly contributing to saving lives. The integration of 4G/5G base stations through a LEO satellite communication network and the proposed use of drone cell towers for urban public safety and disaster recovery scenarios further underscore the societal benefits of these technologies. My contributions have also extended to the broader community, evidenced by the collaboration with Salvamont Romania and Vodafone Romania to expand these life-saving technologies across multiple counties. Recently, two lives were saved in Romania by Salvamont teams, in Valcea county, using the power of drones technology.

6.7.4 Environmental impact

The environmental impact of these contributions is evident in the development and implementation of technologies aimed at improving sustainability and reducing environmental footprints. The innovative inspection of photovoltaic panel infrastructure using drones equipped with thermal vision cameras, in collaboration with INCDTIM Cluj Napoca, showcases the utility of such technologies in preventive maintenance, ultimately contributing to the longevity and efficiency of renewable energy assets. Furthermore, the design and testing of drone systems adapted for mission-critical 5G applications, including their use as network quality scanners for future drone highways, align with efforts to reduce environmental impacts through more efficient and sustainable technologies. In addition, drone-based search and rescue solution considerably reduces the carbon footprint associated with the ground patrols vehicles.

6.7.5 Economic impact

Economically, the contributions have positioned the technologies developed as crucial enablers of future industrial and commercial applications. The proposal and execution of a software platform for the next generation of drones, spanning eight industries, underscore the economic potential of these innovations. The creation of the Vodafone

Innovation Hub has established a significant resource for education and research, fostering the development of technologies that will drive economic growth. Additionally, the practical assessment and testing of the "5G in a Box" system, and its applications in scenarios like mission-critical 5G tactical bubbles, have the potential to influence various industries by offering scalable, efficient, and cost-effective solutions for custom-fit applications in the 5G era.

6.8 Perspectives for further developments

I chose this area of analysis and research for my doctoral program because the rhythm of new technologies development is not linear anymore, the very dynamic trend has an exponential curve and Romania with involvement from passionate professionals must keep-up the pace. The emerging technologies are becoming increasingly important for future directions. At the same time, my professional activity takes place in this area of mobile communications, and it is very important that the network architectures designed are closely linked with deepening the theoretical aspects.

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