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Abstract	This deliverable specifies four showcases and the mechanisms that will be available so that third parties can perform end-to-end experiments through ORCA facilities. In general, the showcases consider SDR, SDN, mmWave high throughput, low latency, PHY flexibility, PHY virtualization and multi-RAT. Specifically, the showcases are 1) high throughput, 2) low latency industrial communication, 3) low latency and high throughput industrial communication and 4) interworking and aggregation of multiple RATs. The showcases consider the concepts of SDR and SDN solutions for future networks, thus, the research community can benefit from the practical communication environment provided by the ORCA structure to develop their applications and research.
Keywords	cognitive networking, software-defined radio, software-defined network, dynamic spectrum sharing, mmWave, multi-radio access technology, vertical slicing

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CO	Confidential to ORCA project and Commission Services	

EXECUTIVE SUMMARY

Due to the increasing demand for wireless communication systems, the future networks will have to deal with ultra-dense cells, bandwidth-hungry applications and diverging Quality of Service (QoS) devices in the same infrastructure. With the objective of providing solutions for these issues, ORCA aims to provide a platform that unifies **software-defined network (SDN)** and **software-defined radio (SDR)** solutions. Consequently, the creation of multiple virtual networks that operate on the same infrastructure will be possible, allowing ORCA to offer end-to-end networking **experimentation facilities** incorporating open, real-time SDR platforms with low runtime latencies, high throughput and versatility.

The goal of this deliverable is to define relevant showcases in order to promote ORCA capabilities. The showcases to be presented cover different aspects of cognitive radio, ranging from the physical up to higher layers. **Showcase 1 focuses in a high throughput mmWave operation**, thereby making available a flexible platform such that the use of more practical antenna arrays and real world propagation conditions be properly investigated. **Showcase 2 focuses in low latency industrial communications**, with objective of enabling flexible low latency-critical SDR experiments for other partners, in which the PHY can be reconfigured in real time. **Showcase 3 focuses in low latency and high throughput industrial communication** by proposing an integrated real-time SDR and SDN approach for the deployment of a service-aware wireless infrastructure. Finally, **showcase 4 aims at interworking and aggregation of multiple RATs**, such that a interworking platform of a 3GPP LTE system together with a new mmWave RAT as well as 802.11 is possible.

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ABBREVIATIONS

5G-NR	5G - New Radio
API	Application Programming Interface
AR	Augmented Reality
ASIP	Application Specific Instructure Set Processor
CSAT	Carrier Sense Adaptive Transmission
CN	Cognitive Networking
DSS	Dynamic Spectrum Sharing
ESC	Environment Sensing Capability
FPGA	Field Programmable Gate Array
HALO	HArdware in the Loop
IoT	Internet of Things
ISM	Industrial, Scientific and Medical
LAA	License Assisted Access
LBT	Listen Before Talk
LTE-A	Long Term Evolution Advanced
LWIP	Low Weight Internet Protocol
MAC	Media Access Control
MSC	Modulation Coding Scheme
MIMO	Multiple-Input Multiple-Output
NLOS	None Line-of-Sight
mmWave	Millimeter Wave
MPTCP	Multi-Path Transport Control Protocol
ORCA	Orchestration and Reconfiguration Control Architecture
OFDM	Orthogonal Frequency Division Multiplexing
QoS	Quality of Service
PHY	Physical Layer
RATs	Radio Access Technologies
REM	Radio Environment Map
RF	Radio Frequency
SAS	Spectrum Access System
SDN	Software-Defined Networking
SDR	Software-Defined Radio
SDWN	Software-Defined Wireless Network
TC	Traffic Class
TXOP	Transmit Opportunity
WLAN	Wireless Local Area Network

1 INTRODUCTION

Due to the increasing demand for wireless communication services, a variety of technologies and standards emerged rapidly, covering different ranges and different licensed and unlicensed spectral bands, such as the 2nd, 3rd and 4th generation of cellular technologies, Wi-Fi, Bluetooth and ZigBee. Three important aspects have to be considered regarding the standard technologies

(1) the number and diversity of wireless devices tends to increase constantly,

(2) running applications have very diverging **Quality of Service (QoS)** requirements and became more critical and bandwidth-hungry, and

(3) many wireless technologies are commonly integrated in the same device, sharing the same physical environment and spectral bands in many cases.

Consequently, some issues are emerging such as the lack of available spectrum for the numerous devices demanding high data rates and the network complexity, since different applications with diverging requirements in the same wireless infrastructure have to be managed.

One promising alternative to mitigate these issues is the **cognitive** radio **networking (CN)** [1] concept, with the feature of monitoring the dynamic behaviour of the network and taking real time actions accordingly. The spectrum scarcity problem is a result of the fixed bandwidth allocation policies adopted currently to manage the spectrum, therefore the CN has a crucial task of improving coordination within a given spectral band and exploring **Dynamic Spectrum Sharing (DSS)** by using idle bands opportunistically.

Many physical layer implementations are based on inflexible Application Specific Integrated Circuits (ASIC). However, to allow flexible physical layer (PHY) transceivers to be deployed, one possibility is to implement these transceivers by means of software on a host computer or an embedded system equipped with programmable hardware, such as Application Specific Structure Set Processors (ASIP) or Field Programmable Gate Array (FPGA). This solution gives rise to the concept of **Software-Defined Radio (SDR)**.

Besides the radio parameters, the CN is also able to adapt the network parameters in order to attain a given performance and QoS, which is very challenging when applications share the same infrastructure and have diverging QoS requirements. Considering that the networks of the actual wireless standards normally needs intense manual work to be configured, it is often not very efficient regarding energy consumption and it is relatively static. The CN is more adequate to deal at the same time with extreme (ultra-low latency, ultra-high throughput, ultra-high reliability) and diverging (low AND high data rate, time-critical AND non-time critical) communication needs. This efficient network management can be accomplished by the **Software-Defined Networking (SDN)** concept that allows the virtualisation of a single physical network into multiple logical network domains, which serves different categories of traffic flows according to their individual QoS needs.

Studies regarding SDR and SDN have been developed substantially in the past years, however there is still a need to merge these two concepts in a unified platform in order to make them feasible in the future networks, therefore the ORCA project has the goal to perform such unification.

1.1 Overview of ORCA approach

Based on the recent evolutions on SDN, SDR and DSS that have been done by isolated communities, ORCA intends to unify these solutions that are mature enough into **end-to-end networking experiments** that can be utilized in several market segments, including manufacturing, automotive industry, healthcare, ambient assistant living, public events, home automation, and utilities.

ORCA will bridge SDR with SDN technology, enabling the creation of multiple virtual networks that operate on the same infrastructure but meet the most diverse and stringent application requirements, which allows ORCA to offer **experimentation facilities** incorporating **open, real-time SDR platforms** with low runtime latencies, high throughput and versatility. Figure 1 depicts the concept of filling the gap between 1) **fast design cycle and high versatility,** but high runtime latency (typically offered by a CPU environment) and 2) **low runtime latency**, but slow design cycle and low versatility (offered by ASIC). The project will open novel frequency bands, by proposing SDR technology at **mmWave** frequencies that is mature enough to be included in networking experiments.

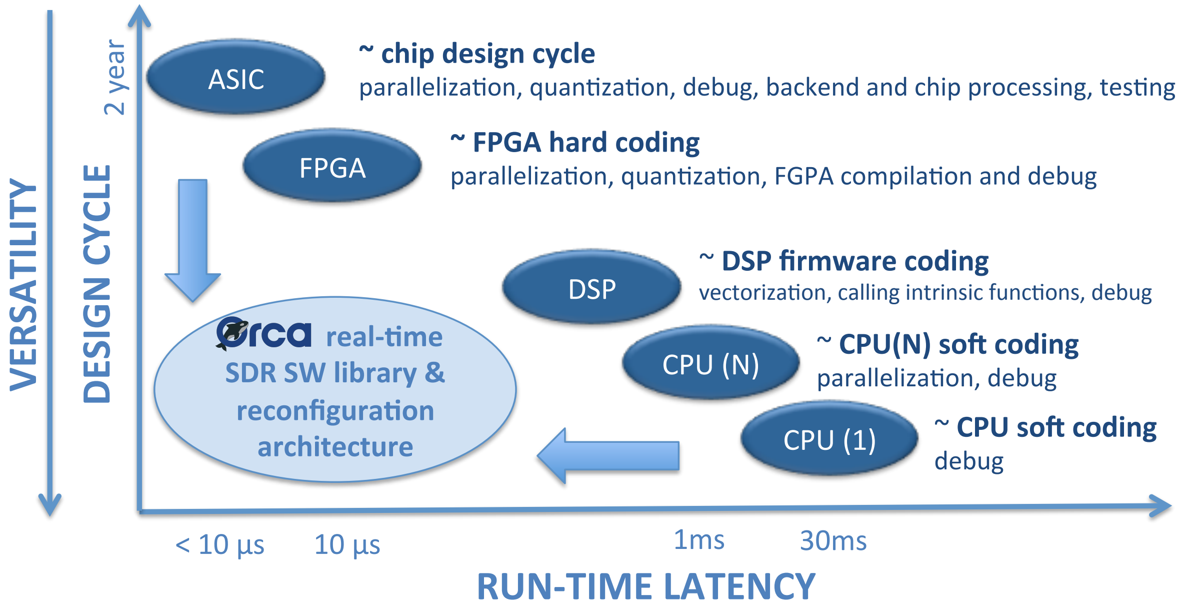

Figure 1: Filling the gap between high versatility and low latency with real-time SDR

Figure 2 presents the main concept of ORCA that covers all aspects of future communications systems. It will promote the virtualisation of the network infrastructure into separate independent network infrastructures, by applying the most appropriate protocols and resource sharing mechanisms for dealing with a specific Traffic Class (TC). This concept is termed **network slicing** and **vertical slicing**. This feature allows the network to deal with very diverse traffic demands, which is a key capability in the future networks. Each pipe in Figure 2 represents a single network slice, which is designed and optimized for the specific requirements of the applications supported by its TC. At the PHY, SDR will enable the radios to have as much flexibility as possible to explore different time, frequency and power resources, utilizing DSS algorithms and mmWave bands. At the Media Access Control (MAC) level, intelligent and dynamic mechanisms will ensure multi-Radio Access Technologies (RATs) aggregation, spectrum sensing, Multiple-Input Multiple-Output (MIMO), precise package scheduling, and other functions. Moreover, at the network level, SDN will allow real-time resource allocation based on QoS requirements of each TC.

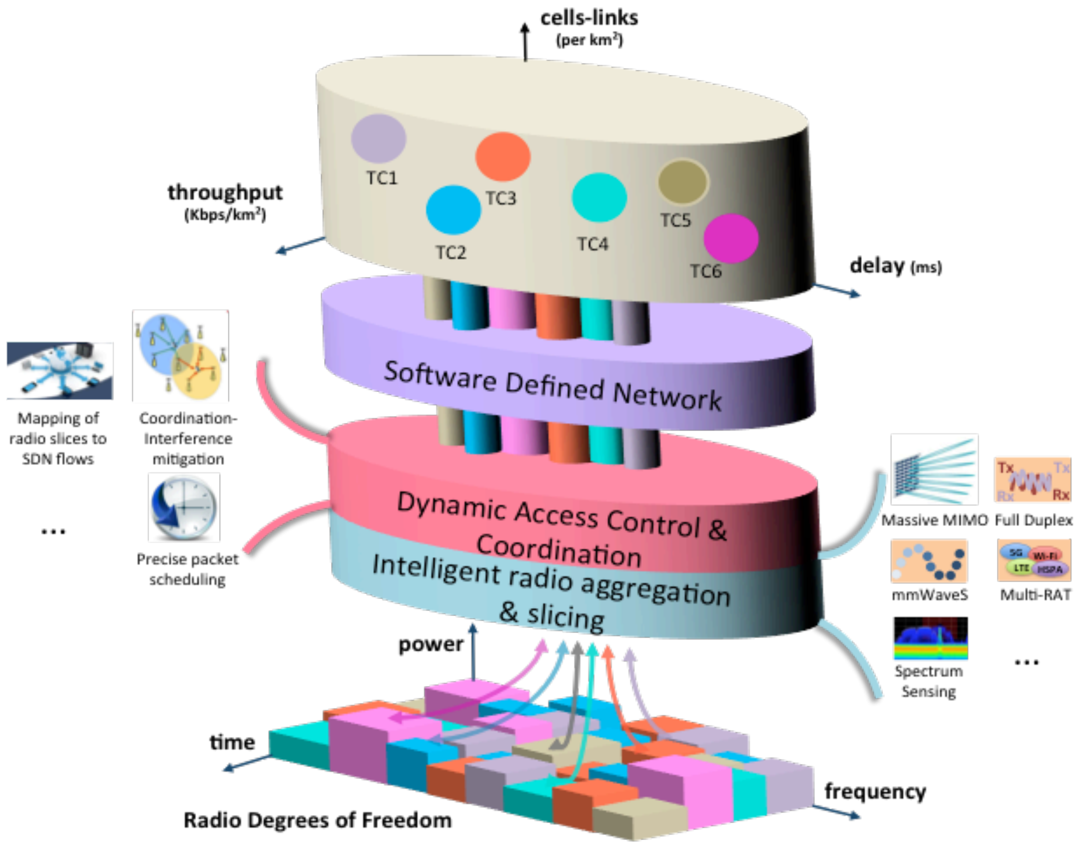

Figure 2: Main ORCA concept of bridging real-time SDR with SDN by exploiting maximum flexibility at radio, medium access and network levels

1.2 ORCA showcases

The ORCA project will support the enhancement of the cognitive SDRs in order to make higher throughput and lower latency feasible. Based on the SDR improvements, ORCA will build a flexible, virtual and multi-RAT network. These objectives leaded to the four showcases described below. The showcases aim to address desired aspects such as high throughput, low latency, interworking and multi-RAT aggregation. The showcases demonstrated by the ORCA partners are promoting the ORCA testbeds and SDR functionalities.

SHOWCASE 1 – Demands for high throughput and dense networks links makes the mmWave technology a key element in the future networks. It will ensure a smooth cooperation of humans and robots in the factory of the future, by enabling Augmented Reality (AR) and virtual reality applications. However, to achieve these goals, a tight co-design of wireless link and mobile network has to be considered, thus this showcase will provide appropriate tools to study solutions for mmWave communications.

SHOWCASE 2 – In order to keep optimizing the factory productions, for example, by automating the transportation of intermediate products between different production steps, the number of autonomously acting robots in the production floor will increase drastically. To accomplish this, the robots need to be remotely controlled with low latency, which is the focus of this showcase. The SDRs will have the capability of increasing spectrum efficiency and robustness due to its adaptability features. In this manner, latency-critical SDR experiments are available for external partners.

SHOWCASE 3 – The future networks will require a flexible PHY and virtualization, in this way the networks will be capable of optimizing end-to-end communication according to a specific demand. This showcase has the objective of showing the vertical slicing concept. It will contribute to the

ORCA project by enabling experiments that need to create multiple network slices that share the same infrastructure and spectrum, and by proposing an integrated real-time SDR and SDN approach for the deployment of a service-aware wireless infrastructure. To achieve these goals, the third showcase will merge flexibility and reconfigurability characteristics from both, SDN and SDR. Note that this showcase aims to attend diversified traffic classes, while the previous showcase only focus on low latency applications. In addition, the two showcases differ in the realization approach, as discussed previously.

SHOWCASE 4 – Exploiting the interworking of parallel RATs is essential for the future networks to work as optimal as possible, since the system performance is increased because the system can opportunistically use multiple heterogeneous infrastructures. Within the ORCA project, the interworking of a 3GPP LTE system together with a new mmWave RAT as well as 802.11 is possible. This showcase will provide a flexible platform such that the community can benefit from the ORCA testbed to develop RAT interworking mechanisms.

2 SHOWCASE 1: HIGH THROUGHPUT

2.1 Showcase summary

In the following showcase, we have identified typical mmWave applications and scenarios, which need to be further investigated. For instance, Augmented Reality (AR), real time high definition video and automated robots in factories will bring a novel range of applications that demand high throughput and low latency, making mmWave a promising solution in these cases.

This showcase will demonstrate a high throughput mmWave system using beam alignment and beam forming. In addition, we define an offer, available for external partners, to test their mmWave PHY and MAC solutions in a realistic environment, such that the RF impairments effects due to the smaller wavelength can be properly investigated.

2.2 Extended showcase description

2.2.1 Background and motivation

Factory of the Future applications are demanding higher data rates to increase the overall efficiency in the production. This includes different areas in the production cycle, like process monitoring but also machine maintenance. The article [2], written by experts from industry, motivates how future high data rate and low latency communication systems play a major role in driving those applications. Especially AR in the factory of the future will have a big influence and is hungry for those future networks to aid remote-live support or pick-by-vision applications.

Main reason for the demands on the network is to reduce the complexity at the receiver side. The idea is to process the images, requiring high computation power and energy, in the cloud rather than in the personal device. This reduces weight and battery life at the client side, if the respective images can be delivered in real-time.

Therefore, the peak user data rates in the networks are expected to rise to the order of 10 Gbit/s. Improving spectral efficiency by using high order modulation and low out of band radiation transmission schemes are not able to mitigate this problem, as the bandwidth in traditional band is limited. mmWave communication promises to meet the throughput demands by the usage of large spans of available bandwidth, allowing higher data rate experience per user in cellular systems [3].

mmWave technologies have the potential to be used in many different scenarios too. For instance, in street canyons that appear in high-density urban areas, mmWave hot spots can be placed such that the spectrum can be reused in different locations frequently. In events like the Olympics, in which the density of people per square meter is enormous, the mmWave technology will strengthen the network access, which is distributed among many small cells. Another interesting application is in fronthaul and backhaul in cases where wired connections are more expensive or not feasible [4].

Given the broad range of use cases that will be explored by the mmWave spectrum in future systems, it is clear that there is a need from the academia and industry to investigate these solutions. In this context, this showcase intends to provide a platform, which enables researchers to investigate mmWave related system aspects.

2.2.2 Problem description

First works focused on the usage mmWave bands for indoor static point-to-point communication like WPAN and WLAN. However in cellular systems different requirements for QoS stability of the communication also in NLOS (None Line-of-Sight) and mobility scenarios have to be made, which are rarely considered yet in practical experiments. The ten-time increase of the carrier frequency compared to traditional bands inherits several problems for communications. Firstly, the channel propagation characteristics are different due to the smaller wavelength. Specifically, the free path loss is higher and blockage and diffraction caused by obstacles are more severe. Therefore, it is necessary to use directional communication with beam alignment for initiating the communication [5]. Afterwards, beam tracking has to be used to keep up the link. In addition, RF equipment is complex to build for these frequencies and is subject to several impairments. For any imaginable application using mmWave bands, the impairments due to propagation conditions previously described are crucial and must be tackled. Another important aspect that has not been considered yet is mobility, even though it is of major concern in cellular systems, it has not been explored very much due to the practical reasons. Further, there is no protocol for cellular applications with beam steering at mmWave frequencies yet. Thus, there is still considerable work to be done in what concerns beam alignment and beam tracking, especially for affordable transceivers. These issues are fundamental for the proper deployment of mmWave solutions with application in augmented reality or massive mobile access in big cities.

2.2.3 Goals

ORCA wants to create opportunities for studying and solving these open issues. Especially the propagation between access point and user terminals needs to be further analyzed. Therefore, the ORCA testbed aims to provide a platform for proper investigation in practical situations.

The mmWave system is based on a real time baseband including relevant parts of the PHY layer. It makes use of beam-switching antennas in order to provide a sufficient amount of receive power. This ability of performing directional communication requires effective beam-alignment and beam-tracking algorithms. Hence, main part of the development is to optimize the beam combinations in the access point and the user device.

2.3 ORCA offer

2.3.1 Motivation

From a practical point of view, it is essential to be certain about which theoretical assumptions regarding RF and channel aspects apply in reality. With the new available spectrum, the throughput will be increased substantially. However, it is necessary to study the robustness and reliability of these systems under realistic beam patterns and RF impairments. Especially mobility has a profound impact in the development on future cellular systems. Additionally, the MAC layer needs to be properly designed for these mmWave systems and is still an open subject.

The ORCA testbed aims to allow feasibility studies on mmWave for external researchers. It will allow experiments on the PHY layer to evaluate the communication performance. As there is currently no real time cellular system standard for mmWave defined, the testbed is an option for supporting the development of such system. This includes MAC aspects as well, since a basic PHY layer is provided to support the experiments.

2.3.2 Approach

Through the TUD testbed, ORCA offers a remote controlled testbed that allows third parties to explore mmWave systems in various ways. It will allow:

1) development and evaluation of an open real time cellular system, which can be parameterized according to specific PHY parameters like MCS or beam indices.
2) channel characterization environment via Hardware-in-the-loop (HALO) with real time radio control operation, allowing to capture datasets for offline evaluation.
3) Mobility is hereby emulated via the use of antenna positioning devices. Further, the use of robots with a mounted mmWave system is considered and will be evaluated.

2.3.3 Demonstrator

This showcase aims to demonstrate the feasibility of configurable RF using mmWave in small cells, making use of beam alignment and beam tracking capabilities of the testbed. Using an antenna rotation table, a mobility scenario can be simulated in a pre-defined way. The testbed is equipped with two moveable trolly structure depicted in the next figure. They are composed by the following components:

- *Sibeam V band transceiver and array*: these components are capable of transmitting and receiving signals over the air in the V band, i.e., 57-66 GHz using the beam alignment feature.
- *Power Supply for Sibeam*: this component is simply the power supplier of the Sibeam.
- *PXI baseband chassis*: this is NI's equipment that provides baseband processing capabilities.

Figure 3: Testbed in a moveable trolley

2.3.4 Mapping to the ORCA KPI

This showcase will contribute to the KPI's 3 and 9. KPI 3 is related to RF configuration suitable for small cell access using directive antennas, and KPI 9 is related to demonstration of parametric reconfiguration over testbed backbone. This showcase matches the KPI 3, in which the used hardware implements directive antennas with beam alignment and beam tracking, being adequate for mmWave small cell access. It is also aligned with KPI 9, in which a parametric reconfiguration over testbed backbone will be demonstrated. By having these contributions in mind, this showcase has the capabilities to support the ORCA partners for performing research towards future communication networks.

2.4 Innovation aspects

2.4.1 Main contributions & achievements

As mentioned in subsection 2.2.2, there is no cellular protocol with beam steering defined yet. With the ORCA mmWave equipment, this showcase intends to provide a study under realistic environment regarding the future high throughput cellular applications. The demonstrator is implemented in parallel FPGA, which has real time inner and outer transceiver signal processing, and comprises the FPGA based radio control interface. It also has a layer 1 driver that works providing data, control and monitoring interfaces between FPGAs and real time controller. Additionally, the layer 1 control measures the channel and configures the physical layer in real time. These operations are done using the beam alignment and beam tracking features, such that the negative effects due to the mmWave propagation will be examined realistically. The demonstrator will illustrate the performance of a low complexity beam alignment algorithm, which reduces pilot contamination significantly. Finally, ORCA will also make available datasets of beam alignment experiments, which can be used by other researchers.

2.4.2 Beyond the state of the art

This showcase will examine how the RF impairments will affect the future high throughput cellular systems. Since there is still no open real time cellular demonstrator available, this showcase and the testbed will have an important role on the development of future cellular systems, providing a real time and closed loop control channel.

2.5 Involved partners & their role

As stated in the problem description, despite lots of progress on the physical layer, there is very little work today in the upper layer protocol to handle features that are specific to 60 GHz communication, such as beamforming. IMEC intends to bridge this gap by bringing in MAC level control and signalling, and look at solutions where multiple users can communicate in a reliable way in the high frequency bands.

NI provides the mmWave baseband including beamforming functionality running on the NI PXI system hosted by TUD. NI will also help with adding required changes to its platform to ease testbed management and configurability. This includes also the provision of additional configuration parameters if needed to control and monitor the NI platform. Furthermore, NI will provide guidance for planning of testbed experiments.

TUD brings in its mmWave testbed, which will be accessible for external experimenters.

2.6 Conclusion

The opening of mmWave spectral bands is crucial to the future communications systems, since the upcoming applications will demand high data rate transmission and cellular cells will become more and more dense. For theses reasons, the ORCA project aims to make mmWave related testbed available to the community in a way that researchers are able to conduct their study through ORCA's testbeds. This showcase was proposed to allow ORCA to achieve this objective, by providing a flexible mmWave PHY structure with capabilities of real time reconfiguration, beam alignment and beam tracking. Since new applications can be evaluated using a realistic platform, the first showcase will contribute to the high throughput mmWave researches of the future communication systems.

3 SHOWCASE 2: LOW LATENCY INDUSTRIAL COMMUNICATION

3.1 Showcase summary

5G and beyond promises the introduction of novel wireless communication use cases where low latency control is crucial, i.e., the tactile Internet [6]. While novel waveforms, typically prototyped by means of SDR, are important here, the low latency can only be achieved by including a tight integration of the PHY with the MAC. This showcase will illustrate how to benchmark novel waveforms and combine them with real-time MAC protocols.

3.2 Extended showcase description

3.2.1 Background and motivation

Wireless communication systems are employed in industrial automation applications [7]. For instance, in the connection of the movable parts of machines and connecting machines in difficult or dangerous environment. The wireless communication can replace the traditional connection using trailing cables, slip rings or sliding contacts. This reduces the cost of installation and maintenance and improves the reliability.

Further, factories and warehouses are moving towards autonomous robots for locating and moving products [8]. Typically, these robots are connected to the network to send and receive status information or updates. In projects like RoboEarth, it is shown how robots can be controlled via centralised cloud systems. For instance, these mechanisms are used to share the knowledge between different robots, to offload processing capabilities to the cloud or to orchestrate them efficiently. In any case, the centralised control system needs to gather all the sensory data from the robots but also ambient data of sensor like CCTV cameras. Based on the input signals, well-balanced decisions can be made and transmitted back to the respective robot.

However, the existing wireless solutions do not offer sufficient performance with respect to real-time and reliability requirements, especially for closed loop control applications [7]. Therefore, low latency wireless communication technology is the key factor for the market penetration of wireless systems in industrial communication systems.

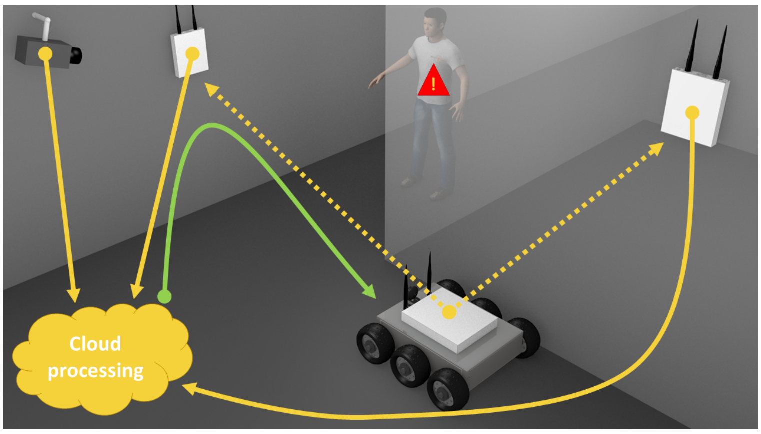

Figure 4: A centralised cloud-based control system integrates sensor data from several sources to make well-balanced decisions

3.2.2 Problem description

Gathering many data wirelessly within certain, predefined delays from a high number of moving sources is difficult. The collision probability of the wirelessly transmitted packets increases exponentially with the number of nodes [9]. Moreover, these factories typically have other legacy devices acting as interfering sources. This results in packets being dropped and therefore required to be retransmitted. Thus, the latency will increase, which violates the QoS requirements for real-time robot applications. In the worst case, stable operation of the control application cannot be guaranteed.

Thus, three different issues have to be solved. The first issue is that interference caused either by the same or by other devices has to be detected and mitigated. The second one is that the overall spectral efficiency has to be maximized to use the spectrum efficiently. Lastly, the application constraints, e.g. latency and throughput, have to be guaranteed with a high reliability to not interrupt the robot operation.

In general, researchers want flexible prototypes with short development cycles. Therefore, software defined radios [10] are used, which typically run all PHY and MAC processing on a general purpose processors as provided by standard PC's. However, the interface between the PC and the SDR is often not fast enough latency-wise to provide real-time control. Especially the in-band full duplex is one of the extreme cases as the interference management has to react almost immediately, because the transmit and receive operation can happen at the same time. As a result, latency critical task have to be ported to FPGA, which requires a specific skillset.

3.2.3 Goals

To solve the above-mentioned problems, PHY and MAC layer innovation is needed. Especially, the QoS in terms of round trip time, latency, jitter and reliability have to be respected. This can be achieved, for instance, by detecting collisions or interference and hence aborting the ongoing transmission. Thus, the retransmission of the corrupted packet can be much faster and saves a considerable amount of energy while reducing the latency significantly [11].

This collision and interference detection needs to run in real-time on the FPGA of the SDRs and the respective nodes have to be equipped with the in-band full duplex technology [13]. As a result, the nodes can simultaneously transmit packets and sense for collisions.

Further, ORCA will evaluate 5G New Radio techniques, which are promising to increase the spectral efficiency and lower the latency by a factor 10 compared to current generation systems. In this case, the GFDM flexible waveform generation framework is used as PHY layer technology, which will be extended by low latency MAC functions. The goal is to have a reliable, low latency transceiver capable of a stable, real-time data link for control applications.

This showcase also aims to provide researchers with specific examples of how to reduce the host latency by offloading functionality like the PHY and MAC to the FPGA and how PHY layer innovations are prototyped on FPGAs [12]. Researchers will be able to develop novel algorithms on top of the presented technologies, to achieve optimization goals for real-time wireless systems.

3.3 ORCA offer

3.3.1 Motivation

Currently many testbeds are utilizing standard, built-in chipsets to conduct network experiments. In those cases, the drivers are extended with customized functions leaving the PHY layer untouched. On the other hand, testbeds focusing on PHY layer experiments have minimized MAC layer to reduce the efforts implementing higher layers.

ORCA wants to bridge this gap by proposing a tight integration between PHY and MAC. This use case will show how, by using the ORCA facilities, it is possible to perform real-time SDR experiments beyond the state of the art. For instance, in ORCA, we will make available a real-time SDR prototype, capable of doing in-band full duplex. As a result, the SDR node can transmit and receive/sense at the same time. This is pushing the limits of real-time control of SDR.

3.3.2 Approach

In the past, latency-critical experiments were infeasible using SDRs experimentation as there is a non-predictable delay from interfacing with the host. One of the reasons is that the signal processing is host based. In this showcase, ORCA will enable latency-critical SDR experiments, by using the FPGA inside SDR for the signal processing related to the physical layer.

Secondly, ORCA will study how MAC functionality can be placed as close as possible or already inside the FPGA, to react quickly to interference issues, for example. More, the co-design of PHY and MAC also enables low-latency communications between a controller and a robot.

Thus, ORCA makes available relevant examples of PHY layer FPGA prototyping or tight PHY/MAC integration for innovative use cases. Third parties can start from the provided examples, and extend them as they find appropriate. Alternatively, they serve as good design examples for concretely novel experiments related to low-latency communications. These experiments can run in the ORCA facilities or the respective projects can be downloaded for evaluation in other testbeds.

3.3.3 Demonstrator

ORCA will show multiple SDRs with in-band full duplex capabilities and collision detection. Shown in *Figure 5* is an early prototype, which will be used for the showcase. The prototype consists of a USRP with Kintex 7 FPGA. The frontend of the USRP is connected to an electrical balance duplexer [14] which cancels the self-transmitted signal and enables in-band full duplex operation. On the FPGA of the USRP we will implement the physical layer with the collision detection capability as well as the MAC layer. The MAC layer will run in a softcore on the FGPA, this allows for real-time operation but also enables researchers to quickly develop new MAC algorithms. In this showcase we will set up a network of these in-band full duplex enabled USRPs and allow them to communicate in real-time with low latency.

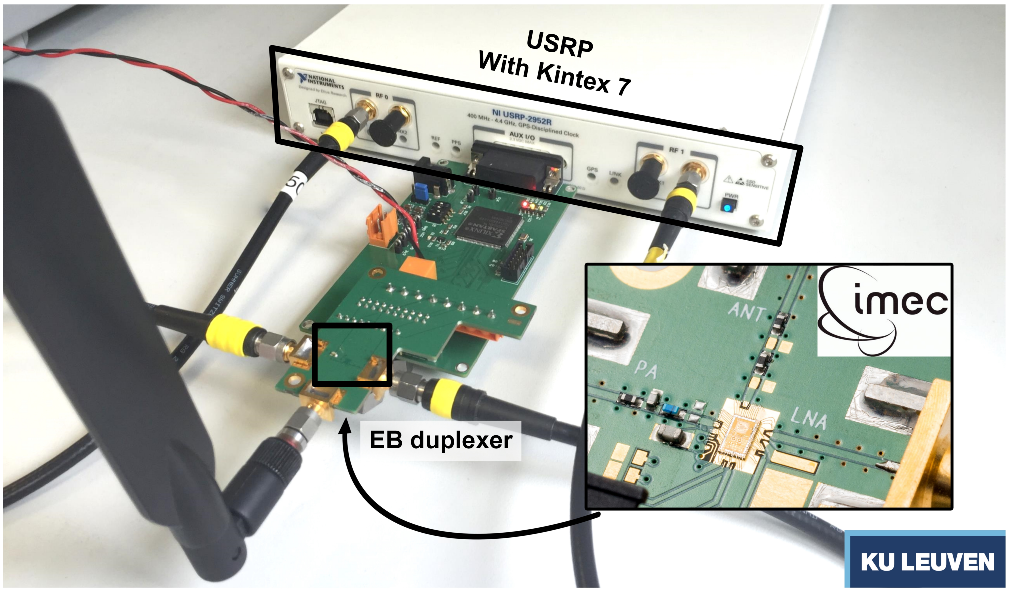

Figure 5: In-band full duplex prototype

Parallel to the previous approach, real-time robot control will be demonstrated and evaluated as presented in Figure 6. In this case, the balancing algorithm of a two-wheeled robot will run on a cloud-like processing platform. Thus, the sensor data has to be transmitted from the robot platform to the access point, processed at the cloud and the respective control signals have to send back to the robot, without overturning.

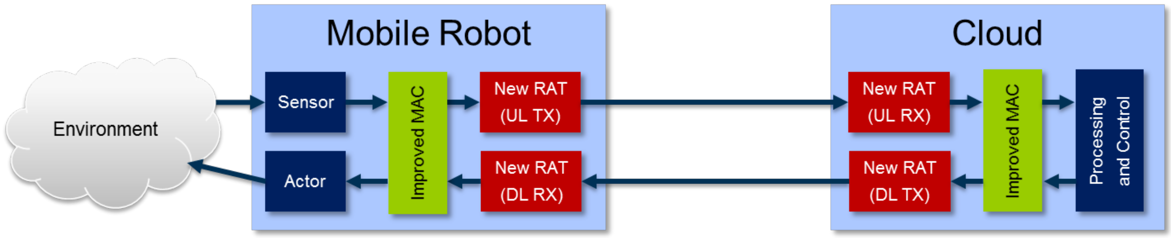

Figure 6: Set-up of the cloud based robot control demonstrator

3.3.4 Mapping to the ORCA KPI

This showcase is relevant for several KPIs in the first year. The first KPI targets low-latency operation beyond the response time of LTE. Objective of KPI 9 is runtime SDR configuration, that includes the reconfiguration of PHY parameter during runtime. The last addressed KPI 15 is about interference control in ISM bands.

3.4 Innovation aspects

3.4.1 Main contributions & achievements

This showcase will contribute with a low latency data link, demonstrating the feasibility of a centralized and real-time control application, including

- Instantaneous collision and interference detection for low latency communication
- Network of in-band full duplex nodes
- Real-time PHY and MAC integration on a software defined radio
- 5G New Radio capable PHY layer

3.4.2 Beyond the state of the art

The current wireless communication systems such as mobile networks or Wireless Local Area Networks (WLANs) lack the real time performance requirements. The delay introduced by these systems ranges between 10 to 100 ms. In order to achieve the end-to end low latency of 1 ms required for industrial automation, the latency of the air interface must be at most 100 µs in one direction, which is in both directions 20% of the total delay [15]. This delay includes the processing delay of the transmitter and receiver, as well as the duration of the packet. The remaining 800 µs are allocated for the upper communication layers, especially the MAC layer. The goal of this showcase is to develop and evaluate FPGA transceiver fulfilling the requirements for low latency communications.

Our software defined radio setup allows experimenters to run real-time MAC layer benchmarks without the need of long development times. Moreover, the collision detection using in-band full duplex allows wireless nodes to vacate the channel within 10% of a typical packet length, saving time and energy, which would otherwise be wasted in collisions.

3.5 Involved partners & their role

TUD will provide the GFDM flexible waveform generation framework running on the USRP-RIO. Further, TUD will study and evaluate MAC aspects of a low latency communication link.

KUL will provide a real-time collision detection prototype, integrating both physical layer and MAC layer on the FPGA.

NI will help with exploiting results from showcase 4 in showcase 2 from MAC perspective, e.g. the connection to the NS3 platform. Furthermore, NI will provide guidance for planning of testbed experiments.

RUTGERS will investigate the RFNoC latency to enable real-time prototyping.

3.6 Conclusion

This showcase provides an experimental basis to study future industrial communication systems. The basis includes open and reconfigurable PHY layer with tight integration of MAC functionalities. It allows the evaluation of closed loop control applications. The main components are in-band full duplex radios, capable of detecting interference and collisions and a flexible physical layer, which can support 5G New Radio features.

4 SHOWCASE 3: LOW LATENCY AND HIGH THROUGHPUT INDUSTRIAL COMMUNICATION

4.1 Showcase summary

The instantiation of customized networks optimized to a specific demand is enabled by the flexibility in the network stack at various layers and by the use of virtualization. This showcase aims to demonstrate the concept of vertical slicing, which is an important concept to attend different demands using a single pool of resources and reconfigurability to design (virtual) networks adapted to each scenario. In order to meet the requirements of different TCs relevant in the factory scenario, it is necessary to create multiple network slices, sharing the underlying infrastructure and spectrum, that deliver ultra-dense OR ultra-high throughput OR ultra-low latency communication. The third ORCA showcase aims to merge the flexibility and reconfigurability abilities from both, SDN and SDR, and propose an integrated real time SDR and SDN approach for the implementation of a service-aware wireless infrastructure through usage of ORCA tools, to instantiate a low-latency, high throughput and high-density network slices on a single SDR infrastructure. This showcase is different than showcase 2 in the sense that 2 focuses on real-time control loop applications, while this showcase targets on a wider range of industrial applications with diverging QoS requirements. Furthermore, showcase 3 focuses on configurability towards end-to-end user application, which is important for SDR and SDN integration.

4.2 Extended showcase description

4.2.1 Background and motivation

There has been a trend for industries to automate their manufacturing process by wireless technologies. This is no longer limited to simple machine monitoring/supervision tasks, but also includes major operations, such as the motion control of heavy machineries, or reaction of emergency situations, leading to the needs of very timely and accurate response. Some control operation requires video monitoring, which pushes the requirement of throughput and response time at the same time. Another important fact in industry automation is that it is a mixture of very diverse equipment, which leverages on different wireless technologies/interfaces. At the time being, these technologies are independent, and jet most of them are coexisting in the unlicensed radio spectrum, leading to mutual interference and unexpected performance degradation.

4.2.2 Problem description

The incorporation of wireless technology into the next generation industrial communication exposes two types of challenges (i) the enhancement in performance (throughput, latency, reliability, etc.), and (ii) the enhancement in the flexibility, in order to cope with the QoS requirements from different traffic types and coexistence with other technologies. The first challenge arises from the broader application range, as mentioned in the previous section, while the second challenge is mainly pushed by the diversity of wireless links and the uncoordinated / inefficient coexistence at the time being.

Behind the scenes, from the developers' viewpoint, another complication exists, that is the choice of implementation platform. As the popularity of SDR rises, and the performance of CPU improves over time, today developers generally choose to have software based radio solutions for its flexibility and fast development cycle. Though for applications or standards which are critical in terms of latency, it is not always feasible to have all functionality implemented in software. However, to go for hardware implementation means immediately a big increase in terms of development time.

Another issue is the lack of agreement on the RF monitoring tools necessary to maintain peaceful coexistence between different RATs. As more RATs and services are introduced in unlicensed spectrum, it is becoming increasingly challenging for operators or regulators to ensure sufficient RF isolation between services, and enforce spectrum access rules.

4.2.3 Goals

This showcase aims to attend different demands using a single pool of hardware resources and reconfigurability to design (virtual) networks adapted to each scenario. In order to meet the requirements of different TCs, it is necessary to create multiple network slices, sharing the underlying infrastructure and spectrum. The flexibility and reconfigurability of radio interface will be achieved on a real-time SDR platform, while the reconfigurability of higher layer network functionality will be achieved in the context of SDN.

As for developers, it is also the goal to speed up the development cycle and find the equilibrium between software and hardware implementation, depending on the requirement of latency, throughput, and etc.

Slicing and reconfigurability of radio interfaces cannot take place without the feedback on the performance (e.g. experienced latency and throughput) and the utilization of the spectrum by other coexisting RATs. It is, therefore, also a goal of this showcase to explore new tools that allow operators and regulatory entities to obtain real time data on spectrum activity in different channels.

4.3 ORCA offer

4.3.1 Motivation

As stated previously, the long development cycle in the field of wireless communication is hindering a fast uptake of new concepts in commercial products. Though many efforts are ongoing to improve flexibility as well as performance of the existing technologies, it takes time for these new features to become ready for the market. One of the motivations here is shortening this development cycle by using a modular design approach and a hybrid solution of software and hardware design, referred to as hardware/software co-design. Such an approach, when offered on open experimental SDR platforms together with the necessary design and experimentation tools, allows experimental validation of new concepts (at any layer in the protocol stack) already in an early phase of the development cycle.

Regulators and industry bodies are becoming increasingly interested in the use of Radio Environment Maps (REMs) and Environment Sensing Capability (ESC) for providing real-time RF measurement information on channel occupancy and spectrum users to databases or spectrum access systems (SASs), avoiding this way, the inefficiencies and limitations traditionally associated to theoretical propagation models or local sensing. The use of ESC can provide mechanisms for fast detection of incumbents, dimensioning of adequate protection zones, and for policing and enforcing that users follow the defined rules of channel access. Furthermore, the fact that ESC collected data can be accessed remotely allows regulators and operators to cut costs on sending specialized staff to the terrain for troubleshooting. The main obstacle to a more extended use of REM/ESC has been the high costs associated to the deployment and maintenance of a dedicated sensing network. We aim to explore how the aforementioned principles and concepts of radio slicing, modularity, short development cycle and remote configurability allow the instantiation of software-defined RF monitoring networks on infrastructure that is also shared with other communication services.

We aim to offer the showcase itself as an exemplary solution for flexible radio implementation, including optimization of radio resource utilization and intelligent network control. Wireless developers can start from this showcase for their own developments.

4.3.2 Approach

This showcase aims to merge the flexibility and reconfigurability abilities from both, SDN and SDR, and propose an integrated real-time SDR and SDN approach for the implementation of a service-aware wireless infrastructure through usage of ORCA tools, to instantiate a low-latency, high throughput and high-density network slices on a single SDR infrastructure. In order to realize the SDN-SDR integrated vision, ORCA will adopt the principle of separation of data plane, control plane (also called 'controller' plane in SDN terminology), application plane and management plane. Users of the ORCA facility will be able to:

- use the offered radio framework by interacting with the control, management and data plane for their own application layer development.
- achieve fast implementation of PHY and MAC, but benefit from the modular design approach, e.g. the concept of software controlled hardware accelerator.
- use the interfacing between SDR and SDN for customized network implementation.
- implement flexible RF monitoring mechanisms and tools in SDR that offer better context awareness, essential for optimizing spectrum resource allocations

4.3.3 Demonstrator

The demonstrator is driven by industrial applications with diverse traffic classes, in particularly we plan to include video monitoring (high throughput), control loops (low latency), and emergency stop (very high reliability) applications in this demonstrator. Behind the scenes, these applications are supported by multiple radio access technologies running one physical radio hardware. From IMEC side, the selected hardware is the Xilinx Zynq 7000 SoC in combination with the FMCOMMS2 radio frontend. The Zynq SoC contains a duel-core ARM processor and a large FPGA, while FMCOMMS2 is tuneable across wide frequency range (70 MHz to 6 GHz) with a variable instantaneous bandwidth till up to 56 MHz. A picture of the selected hardware is shown in *Figure 7*.

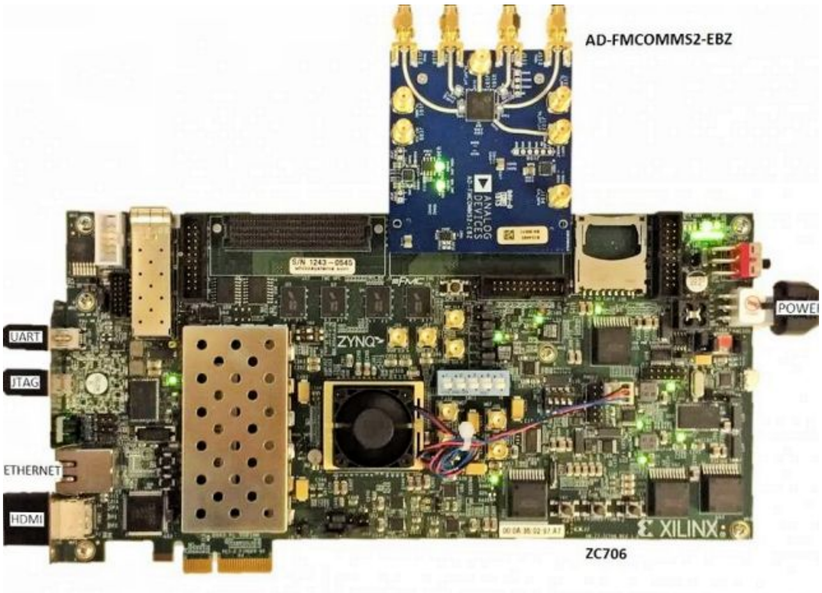

Figure 7: ZynQ SDR

The realization of the radio interface will be achieved on the embedded system, meaning no processing assistance is needed on the host computer. More specifically, the intensive processing tasks will be offloaded to various hardware blocks in an FPGA, which are referred to as 'hardware accelerators', while the connection or data plane between accelerators is controlled by the ARM processor on board. Alternatively, the connection between certain accelerators can be made directly (without going through ARM) for timing-critical path. This is essentially the concept of RFNoC, which will be integrated with the support from University of Rutgers. The initial technologies we foreseen for virtualization include LTE, IEEE 802.11 (OFDM-based PHY), and IEEE 802.15.4.

Eventually we aim to provide a framework where other radio access technologies can be easily plugged into the system, using the concept of the shared hardware accelerators. In the demonstrator, we also foreseen non-collaborative or unknown transmitters, which will be recognized by radio environment monitors developed by TCD, please refer to the next paragraph for details. The output of the monitoring instance will be used to improve the slicing of radio resources, such as spectrum, time. In this way, we effectively demonstrate the mutual interference between the targeted technologies is better controlled via the concept radio virtualization.

The demonstrator of TCD focuses on the concepts of radio virtualization and infrastructure sharing in the creation/deployment of environment sensing capability (ESC) networks for spectrum sharing and frequency allocation planning. TCD plans to develop signal classification algorithms based on deep learning, which the ESC network operator will use to discriminate signals emitted by different users of the spectrum. A possible application is the ISM bands (2.4 GHz or 5 GHz) or the 3.5 GHz band that accommodate multiple RATs. TCD's developed signal classification algorithms could help infer what are the likely sources of interference (e.g. LTE-U, WiFi, ZigBee or radar) experienced by users and contribute to better overall spectrum resource management. The developed classification solutions (e.g. convolutional neural networks) will run on the host PC, either in the CPU or GPU, and their software can be efficiently compressed, transferred, and run across different virtualized radio nodes of a network. The chosen RF front-end hardware for this implementation are the USRP X and B series.

TCD will also demonstrate radio virtualization of different radio access technologies using SDR on the host PC. Some of the envisioned technologies may include LTE and IoT standards, whose MAC protocols' latency requirements are lenient enough to avoid programming the front-end's FPGA. While less performant than FPGA or ASICs, host PC-based SDR solutions can open new doors for the reconfiguration of RATs in a dynamic, flexible way. It may also operate as a complement and extension of the solutions provided by IMEC.

Through the use of a common control plane, experimenters will be able to remotely instantiate and configure different radio technologies in the SDR nodes of a testbed. These radio technologies include WLAN and Zigbee, provided by IMEC, and the RF monitoring tools provided by TCD. Experimenters may optionally apply the data gathered by the TCD's RF monitoring tools to reconfigure other RATs' parameters or resource allocation strategies, such as transmission frequency, bandwidth, power intensity, and time slots in case coexistence with TDMA like RAT are being considered.

4.3.4 Mapping to the ORCA KPI

In the first year activity, this showcase is relevant to 2 KPIs, which are KPI 15 (interference control in ISM bands), and KPI 11 (SDR and SDN integration) respectively. More specifically, KPI 15 is about demonstrating coexistence between transmissions with different waveforms in the ISM bands. KPI 11 is about instantiating 2 virtual wireless networks with different characteristics sharing the same infrastructure and spectrum.

Our demonstrator includes the virtualization of multiple radio technologies on one platform, this is the action we take for KPI 11, while the effective slicing of radio resources to avoid interference is aligned with KPI 15.

4.4 Innovation aspects

4.4.1 Main contributions & achievements

The following achievements are targeted in this showcase:

- Virtualization of radio access technologies,
- Providing flexible monitoring and analysis tools for resource management,

European Commission

- Optimization of radio resource utilization,
- Concurrent support of diverse traffic classes, especially high throughput in combination with low-latency and high-reliability applications.

4.4.2 Beyond the state of the art

Although the field of SDN and SDR exist, there is not yet joint development effort, to the best knowledge of the consortium. The topic of integrating SDR and SDN is very new on itself, therefore we are pushing for a first step in this direction.

The virtualization of radio interfaces and its underlying technologies can be seen as one way of integrating multiple radio access technologies (Multi-RAT). We believe the concept of assigning physical layer resources, radio technologies, and many other parameters to optimally serve different traffic classes on the application layer is an important add-on in this subject.

In the RF monitoring topic, current methods for distinguishing between different waveforms are based on the combination of decision trees with feature detection algorithms. The complexity of these methods tends to not scale well with the number of waveforms coexisting in the same band, as they practically require one sensing circuit per each RF feature that needs to be analysed. Furthermore, these methods are difficult to design for the case of RATs with multiple modes of operation or parameter configurations. Another important issue associated to RF monitoring/ESC networks is the cost of their deployment. While there is prior work and discussions on the use of crowd-funding concepts and incentives to turn individual radio nodes into sensing devices that report their data to spectrum management databases, little has been done bridging these works with the aforementioned concepts and principles of SDR, SDN and slicing. We believe that existing tools in the field of machine learning can provide valuable information to accelerate this integration, as well as the design and deployment of new, generic, more powerful sensing methods for ESC networks.

4.5 Involved partners & their role

In this showcase, IMEC takes part in virtualization of multiple radio technologies on embedded SDR platform, which requires support from Rutgers to integrate with the RFNoC framework for the trade-off between flexibility and speed. TCD focuses on radio environment monitoring, which provides essential input to slice and allocate the resources efficiently.

4.6 Conclusion

The motivation of this showcase is twofold: one is to improve wireless network performance, in terms of QoS, throughput, flexibility, reliability, latency; and the other is to reduce the effort of implementation, such as the learning process of complicated system and development cycle.

We aim to demonstrate that the network performance can be improved by enhancing the overall flexibility and optimizing the radio resource utilization, which are further realized by the virtualization of radio interfaces and the radio environment monitoring.

We aim to demonstrate that the development cycle of wireless technologies could be reduced, with the aid of module architecture design, the appropriate distribution between software and hardware implementation, and the separation of data and control plane.

5 SHOWCASE 4: INTERWORKING AND AGGREGATION OF MULTIPLE RADIO ACCESS TECHNOLOGIES (RAT)

5.1 Showcase summary

Showcase 4 embraces general coordination strategies when using multiple radio access technologies (RAT) such as 3GPP LTE and 802.11 WLAN but also future 5G - New Radio (5G-NR). One specific challenge that is addressed is to understand better the different interfacing options and practical constraints when using different RATs. Therefore, the approach is to first enabling an LTE and 802.11 prototyping platform to start investigations and experiments for the interworking of these systems. In a second phase a 5G-NR based system can be included into the prototyping platform to extend the results and enable a holistic comparison of the different RAT interworking options that will help to understand better the trade-offs and achievable gains.

5.2 Extended showcase description

5.2.1 Background and motivation

In today's networks multiple radio access technologies are available to provide the users the required services: the cellular 3GPP LTE as well as the Wireless LAN 802.11 standard, which means that the heterogeneous network slices can also opportunistically rely on multiple heterogeneous infrastructures. Throughout the concept phase of the new 3GPP 5G standard there is a consensus that there will be a path of LTE evolution that is backward compatible as well as next generation RAT that includes completely new disruptive technologies. The use of those interworking techniques is required because as of today it cannot be foreseen that there will a single RAT in the future that can be used for all spectrum bands addressing the diverse set of anticipated service requirements. One specific challenge is to enable the interworking of parallel RATs to exploit the benefits of those individual options and deliver the required services to the user.

5.2.2 Problem description

In *Figure 8* possible RAT interworking options between 3GPP LTE and 802.11 as well as new 5G systems are depicted. To use additional spectrum, in order to increase the overall throughput of the end-to-end application, is one major goal of available or researched interworking techniques. Therefore, standardization bodies have been discussing and releasing options to aggregate LTE and 802.11 RATs to extend the licensed LTE spectrum to offload traffic to unlicensed spectrum [16], [17]. Examples are:

- MPTCP: Multi-path TCP allows to split/aggregate data traffic using a corresponding proxy in the IP network.
- LWIP: LTE WLAN Radio Level Integration with IPsec Tunnel to split/aggregate the data traffic above layer 2
- LWA: LTE-WLAN Radio Aggregation to split/aggregate on PDCP level
- LTE-U: Using LTE RAT in unlicensed bands switching off consecutive TTIs to allow 802.11 to transmit keeping the synchronous LTE framing
- LAA: Using LTE RAT in unlicensed bands but implementing 802.11 related listen before talk procedures resulting in asynchronous LTE frames

As for aggregating 3GPP LTE with a new 3GPP 5G-NR RAT (e.g. in mmWave or sub-6GHz spectrum) available options that has been discussing are [18]:

- Dual connectivity: Allows to split/aggregate traffic on PDCP level

- Carrier aggregation: Allows to split/aggregate traffic on MAC level

In particular for 3GPP 5G-NR non-standalone mode these aggregation types are of interest where the target is to complete the corresponding work item by March 2018. [Reference: 3GPP March Plenary Summary].

In general, one can distinguish between different levels of RAT interworking:

- Split/aggregate data traffic in IP network using completely separated RATs
- Split/aggregate data traffic on layer 2 / MAC but using different RATs in licensed and unlicensed spectrum
- Use one RAT (e.g. 3GPP LTE) in licensed and unlicensed spectrum

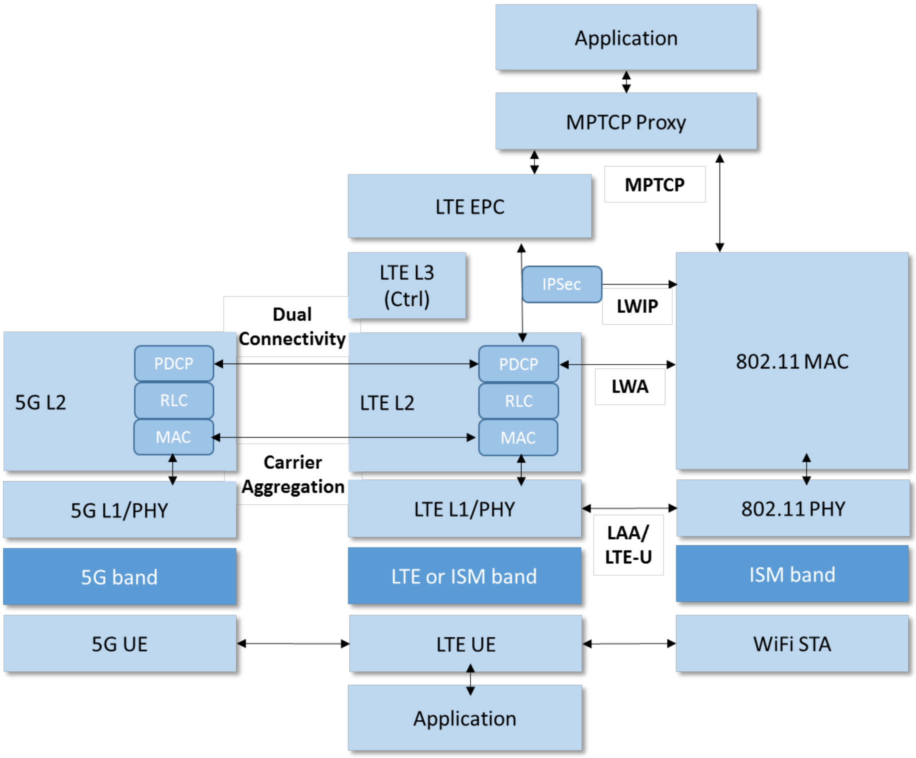

Figure 8: RAT Interworking Technologies

The high number of RAT interworking options requires a thorough understanding of the trade-offs w.r.t. achievable gains and practical constraints when dealing with large scale deployments of different technologies. Some challenges that needs further investigation with underlying practical experimentation are for examples:

- Multiple RATs share one physical medium at the same time, therefore new techniques are needed to provide resource sharing in time or frequency domain
- The interworking of quite different types of communication systems is proposed e.g. scheduled (cellular networks) and ad-hoc (802.11) communication systems
- Higher communications layers such as L2, L3 and Core Network needs to handle
    - the configuration of multiple RATs (control plane)
    - the data split and aggregation to/from multiple RATs (user or data plane)
    - split of control and data plane

5.2.3 Goals

Within the ORCA project the interworking of a 3GPP LTE system together with an 802.11 RAT as well as a new 5G RAT in a practical experimentation setup is targeted. The flexibility of the experimentation platform enables researchers to investigate how the different RATs can interwork, e.g. at which level the data could be aggregated and what are requirements for data and user plane in terms of radio resource management and control. Measurement results in the real-time testbed will gain the understanding of the general requirements of RAT interworking including all aspects and layers of a wireless transmission chain.

5.3 ORCA offer

5.3.1 Motivation

While in the previous section the overall ORCA goal is outlined, in the subsequent sections options for interworking between 3GPP LTE with 802.11 are described in more detail that are targeted within the first year. Investigating 3GPP LTE and 802.11 interworking and coexistence techniques will help to understand the general trade-offs w.r.t. offloading traffic to unlicensed spectrum using the available options. These results can also be used to understand the future aggregation of LTE and 5G-NR better. Furthermore, when doing practical experimentations with the available ORCA SDR prototyping platform the reliability of measured results is increased including all practical constraints for a real end-to-end link.

5.3.2 Approach

By offering a neutral platform that addresses research on coexistence between 3GPP LTE and 802.11, within this showcase ORCA helps the experimenters to drive experiments and find solutions for interworking of different parallel RATs. Neutral here means, that the coexistence-IP does not relate directly to 3GPP LTE or 802.11, because the focus is on channel access framework. Essential parameters are configurable such as the energy detection threshold and the contention window size for the listen-before-talk procedure and transmit opportunity (TXOP) for the number of consecutive transmitted LTE subframes. Most methods, either already proposed or envisioned in the future, can be implemented using the offered prototyping platform. For example, users can:

- do neutral measurements using LTE and 802.11 using E2E connection and data aggregation / Split on higher layers using separate spectrum
- do neutral measurements using LTE and WiFi coexistence on same spectrum using several configuration parameters such as carrier frequency, resource allocation, LBT thresholds, duty cycles etc
- find good operating points for deployment-specific use cases and scenarios
- research towards the convergence of scheduled and ad-hoc wireless systems

help community to get better understanding of what fair coexistence might mean.

5.3.3 Demonstrator

A system sketch of the provided NS3-based SDR prototyping platform provided by NI is shown in *Figure 9*. The architecture consists of three main elements:

- Physical layer implementation on NI's FPGA based SDR platform in LabVIEW [19]
- Upper layer implementation of adapted NS3 C++ code running on NI's Linux RT [20]

The LTE branch is described in [21] that is based on NI's LTE Application Framework [22]. Both, eNB and UE with bi-directional uplink and downlink connection are supported. The underlying SDR platform is based on USRP [23] where several frequency ranges are available, e.g. 120MHz [24] as well as PXI with a corresponding controller with NI Linux RT [25] The used NS3 LTE module includes a Layer 2 and Layer 3 implementation as well as an EPC [26]. Furthermore, NS3 can be used as main application that instantiates a complete EPS but also other components like and client / server applications, IP network components as well as 802.11 nodes that are in the 802.11 branch in *Figure 9*. These are connected to NI's 802.11 Application Frameworks [27] that can run on the same NI SDR platform as the LTE branch. Both, the access point as well as station functionality supporting a bi-directional transmission is available. For the LTE and 802.11 Application Frameworks several configuration parameters are available such as:

- Carrier frequency
- Resource allocation
- MCS
- Transmit power

Moreover, the NS3 LTE module provides e.g. flexibility to:

- Use several instantiations of LTE and/or 802.11 modules
- Use different MAC scheduler implementations

In general, several loopback modes are also available e.g. connect the MAC of NS3 eNB and UE directly without using the PHY and the Radio. This allows for faster simulations and helps with the implementation of new functionality. In general, it is worth mentioning that the described prototyping platform allows for end-to-end experiments using a real-time cable PHY/MAC meaning that the timings required for LTE (e.g. Transmission Time Interval) and 802.11 (e.g. ACK timing) are achieved.

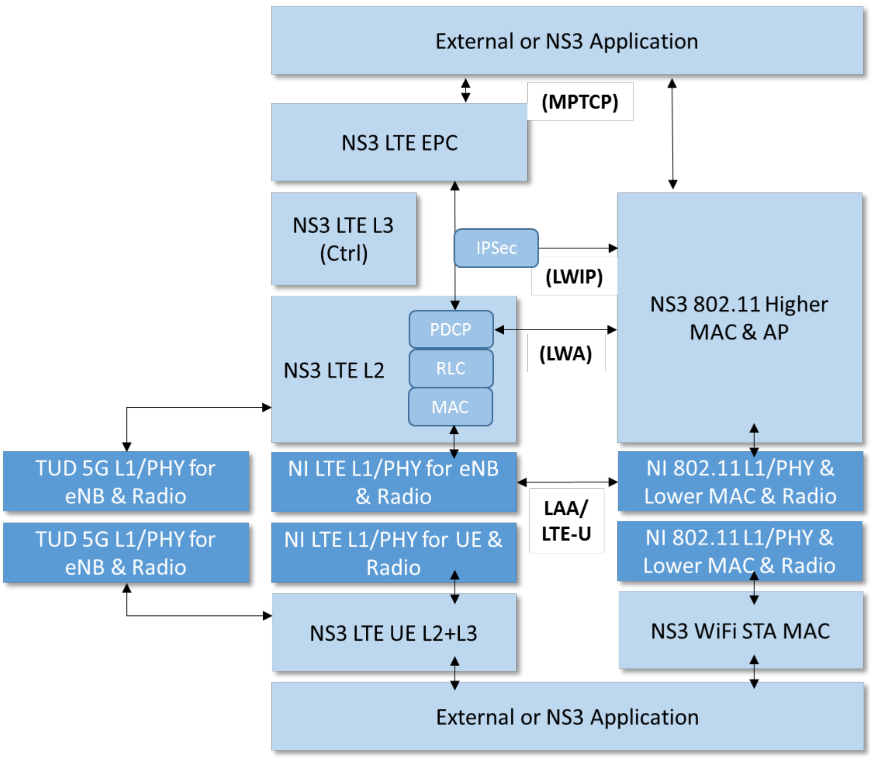

Figure 9: NS3 based Prototyping Platform

To test LTE – 802.11 coexistence with respect to LAA & LTE-U features, an extended LTE PHY exists that includes the required LAA and LTE-U functionality [28]. This can be used as a starting point for interworking studies between LTE and 802.11 networks using a complete end-to-end system with NS3 providing the LTE and 802.11 upper layers and the network elements. Experiments could focus on channel access framework investigating:

- LAA - Configurable LBT cat.4
    - Configurable energy detection threshold
    - Configurable contention window size
- LAA - Configurable discontinuous transmission (DTX)
    - Configurable TXOP (number of consecutive transmitted subframes)
- LTE-U - Configurable duty cycle
    - Further the software architecture is ready for extension towards carrier sense adaptive transmission (CSAT), which could be a possible feature extension for open calls within ORCA

In addition to the available features of the prototyping platform also other data aggregation techniques (marked with braces in *Figure 9*) are possible, like changing the NS3 C++ code and keep the PHY and Radio with the corresponding infrastructure. This will allow a rapid prototyping and experimentation of LTE and 802.11 interworking techniques.

Furthermore, TUD provides a 5G based physical layer implementation that includes features for flexible configuration of the waveforms and frame numerology. With this option in addition to LTE and 802.11 interworking techniques researchers can also investigate the impact of deviating from the LTE frame structure and numerologies to study the impact on coexistence scenarios. Important parameters that differ from the LTE physical layer and can be flexible configured are:

- Number of subcarriers and number OFDM symbols per subframe
- Cyclic prefix length
- Modulation pulse and window length

5.3.4 Mapping to the ORCA KPI

The first-year activity with investigating and extending the SDR platform for parallel LTE and 802.11 interworking and coexisting techniques maps to KPI 15 (Interference control in ISM bands). Further extensions of the SDR platform w.r.t. to 5G-NR interworking option address KPI 13 & 14 (Inter-RAT coordination) as well as KPI 16 (Multi-RAT data aggregation).

5.4 Innovation aspects

5.4.1 Main contributions & achievements

The main achievements targeted in this showcase are:

- Joint LTE and 802.11 prototyping platform that allows for interworking and coexistence experiments
- Joint LTE and 5G-NR prototyping platform that allows for interworking and coexistence experiments
- Better understanding of trade-offs when using different Multi-RAT coordination and data aggregation techniques with a real end-to-end over the air prototyping platform

5.4.2 Beyond the state of the art

Although many interworking and coexistence techniques e.g. between LTE and 802.11 has been discussed and standardized, real experimentation results are often missing because e.g. either LTE or 802.11 prototyping systems are available only, but not both. The same holds for LTE and 5G -NR. However, to proof that the anticipated performance gains translate into reality joint experimentations and measurements are necessary. Furthermore, for a fast test of new algorithms and ideas the prototyping system should be modifiable in terms of parameter reconfiguration as well as the source code itself. Those requirements are fulfilled by NI's prototyping platform using latest SDR technology with a unique tool flow combining hardware and software development as well as a wide range of different processing and RF options. Furthermore, with the connection of NI's SDR platform to the higher layer NS3 network simulator various deployment and test scenarios are possible that allow for experiments that have not been possible so far.

5.5 Involved partners & their role

NI:

- Provides the system prototype for 3GPP LTE and 802.11 interworking studies:
    - LabVIEW based 3GPP LTE and 802.11 physical layer implementations running on NI's SDR platform using USRP and PXI including extensions allowing for LAA / LTE-U tests
    - Connection of 3GPP LTE and 802.11 physical layers to NS3 upper layers using a flexible MAC-PHY Application Programming Interface (API) including interfaces for E2E user data transmission

TUD:

- External access of prototyping platform with FIRE tools
- LabVIEW based 5G / GFDM physical layer implementation

RUTGERS:

- Provide and support with APIs for network-assisted spectrum coordination of RANs such as 802.11 and LTE

5.6 Conclusion

Within showcase 4 the goal is to gain insights into interworking techniques between multiple RATs such as LTE, 802.11 as well as 5G-NR. After the description of the problems and challenges with current systems it is explained how ORCA intends to address the needs of additional research and experimentation using NI's SDR prototyping platform. Here a phased approach is chosen. Within the first year a prototyping platform will be made available that allows for investigating mainly LTE and WLAN interworking techniques. At this stage a 5G physical layer extension from TUD will already be integrated that can be used to conduct early coexistence tests. Within the second year the prototyping platform will then be extended with a 5G-NR based system including upper layers to enable experiments that will help researchers to understands the gains and practical constraints of the different approaches discussed. While the goal is to provide a platform for researchers to enable external experiments within the open calls for every milestone, essential features and selected interworking principles are demonstrated.

6 CONCLUSIONS

The future communication systems will have to deal with numerous and diverse devices connected to the network, which will have very diverging QoS requirements. Also, applications that need high data rates will become common and many wireless technologies will be integrated in the same device. Naturally, this new scenario forces the network to have different strategies to serve its users properly. The cognitive networking (CN) has emerged as a promising solution, whose general idea is to allow the network to allocate its resources in an intelligent and dynamic manner. The CN includes the Software-Defined Radio (SDR) at the PHY layer, for instance, the radio should be able to use the spectrum dynamically according to its needs. Besides, the higher layers will use the Software-Defined Networking (SDN) concept that allows the virtualisation of a single physical network into multiple logical network domains, which serves different categories of traffic flows according to their individual QoS needs. Since the research community has performed the developments regarding SDR and SDN separately, the ORCA project aims to bridge the two concepts and to provide end-to-end networking experiment platform in order to contribute to the development of novel applications.

This document described how ORCA will achieve its contributions through the definition of four showcases, exposing the possibilities in terms of end-to-end experiments that third parties can perform using ORCA equipment. In general, SDRs will be available to provide high throughput, low latency, flexible, virtual and multi-RAT networks.

SHOWCASE 1 – This showcase will focus in a high throughput communication systems using a mmWave link with beam alignment and beam tracking capabilities, which will be important to test novel applications under a realistic mmWave scenario.

SHOWCASE 2 – The second one will focus on low latency industrial communication experiment. By using real time controlled SDRs, this showcase will contribute to latency-critical experiments.

SHOWCASE 3 – The third showcase will focus on low latency and high throughput. By proposing a integrated real-time SDR and SDN approach, service-aware wireless infrastructure experiments will be possible.

SHOWCASE 4 – The last showcase will focus on interworking and aggregation of multi radio access technologies (RATs). The flexible platform demonstrated by this showcase will allow the development of RAT interworking mechanisms.

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