Orchestration and Reconfiguration Control Architecture

ORCA- a 5G Experimental Environment

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***Abstract*—The control mechanisms that are provided today in wireless technologies are not adequate to deal 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. Interesting evolutions are happening at different levels that enable the creation of parallel network slices, each slice forming a different network sharing the underlying wireless infrastructure and spectrum. The overall ORCA vision is to drive end-to-end wireless network innovation by bridging real-time Software-Defined Radio and Software-Defined Networking, exploiting maximum flexibility at radio level, medium access level and network level, to meet very diverse application requirements.**

Keywords—SDR; reconfigurability; vertical/network slicing; multi-RAT; mmWave; end-to-end commnication.

I. INTRODUCTION

Many market segments (such as manufacturing, automotive industry, healthcare, ambient assistant living, public events, home automation, utilities, etc.) require wireless innovation. Although each market segment is characterized by specific applications and services, the demands for applications and services within the single market segment can be very diverse. An illustrative example is a manufacturing environment where different types of wireless communications are required going from very low latency, low data rate and ultra-low latency closed loop communication between (parts of) machines, real-time 3D video-driven interaction between collaborative robots and humans, to non-time critical downloads of large data volumes for updating the software of machines. In many cases different applications and services have to share the same wireless infrastructure and the same spectral bands, making it really challenging to meet the very diverging QoS (Quality of Service) requirements simultaneously. The control mechanisms that are provided today in wireless technologies are not adequate to deal 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. Interesting evolutions are happening at different levels that enable the creation of parallel network slices, each slice forming a different network sharing the underlying wireless infrastructure and spectrum:

At the networking level Software-Defined Networking (SDN) decouples the network control and data plane forwarding functions, enabling directly programmable network control giving diverse network services to a variety of applications. Such an approach allows virtualizing a single physical network into multiple and heterogeneous logical network domains, each domain serving a certain category of traffic flows in the most appropriate way. Such an approach is very encouraging, but has been basically designed for wired networks1 and mainly involves the higher layers of the protocol stack (layer 4 to 7). It is primarily providing transport capacity and service differentiation up to the edge router of wired networks.

At the radio level, we have observed the emergence of Software-Defined Radio (SDR). An SDR is a radio communication system where transceiver components that are typically implemented on hardware (e.g. digital mixers, filters, equalizers, modulators/demodulators, multiple antenna techniques etc. implemented in an ASIC (application-specific integrated circuit)) are instead implemented by means of software on a host computer or an embedded system equipped with programmable hardware like ASIP (application-specific instruction set processor) or FPGA (field-programmable gate array). The concept of SDR is very encouraging for the development of state-of-the-art physical layer (PHY) functionality, because software programming allows much faster development cycles. The main problem with software environments is the slower sequential execution of algorithms, even when multi-core or many-core CPU (central programming unit) platforms or GPUs (graphics processing units) are used, in contrast to a very fast execution and a very high degree of parallelization in an ASIC, ASIP or FPGA. For

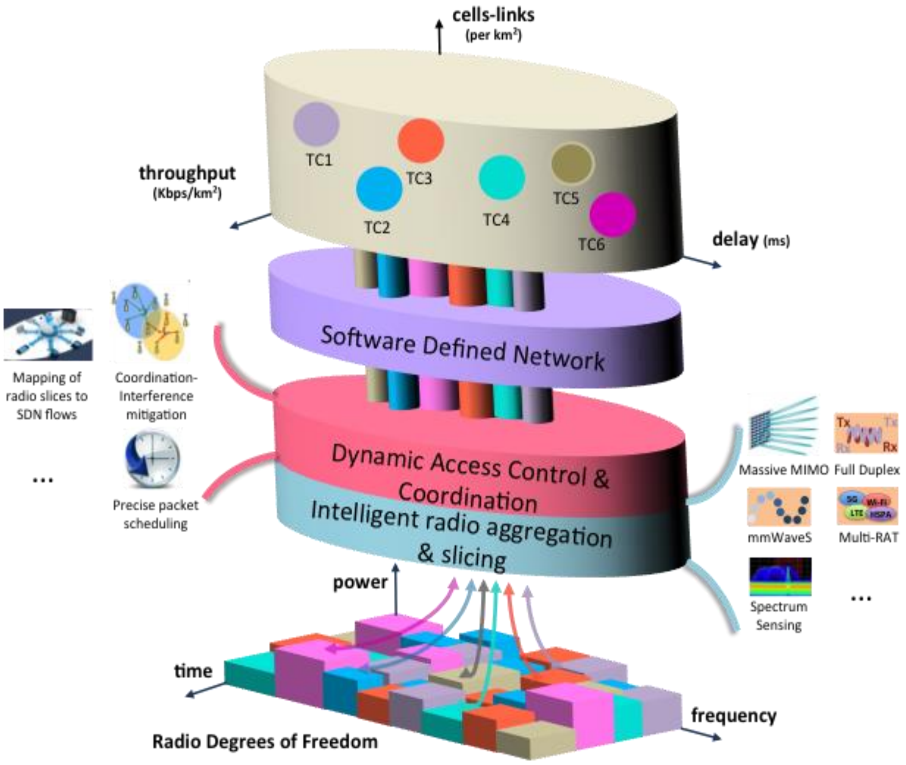

Fig. 1 Network innovation driven by ORCA

this reason SDR development has so far mostly been limited to none real-time physical layer development, as software implementations do not always offer the fast execution times that are required for true networking experimentation (for example requiring fast acknowledgment of MAC frames within a few microseconds). Recently we observe limited yet increasing efforts to code more and more transceiver functionality on hardware, trading software flexibility for faster execution times, at the cost of higher design time efforts.

Parallel to the trend towards more flexible implementations of the radio functionality (SDR), we see the need to use the scarce wireless spectrum dynamically and opportunistically, together with the need to develop technology to make use of higher and more frequency bands. Dynamic spectrum sharing is one of the main applications of Cognitive Radio (CR) while using higher frequency bands is evidenced by the current emphasis on mmWave wireless technology. The early CR community focused mainly on SDRs that flexibly change the centre frequency of their operating channel, while we now see a trend towards even more advanced and flexible wireless technology, including Massive MIMO, full duplex, mmWave, novel waveforms and various collaborative spectrum sensing algorithms.

To enhance the SDN concept towards wireless networks and dynamic spectrum sharing, it needs to be extended with lower layer control (at layers 1 and 2) and take into account the (often very) dynamic behaviour or wireless links and detailed information about interference and spectrum occupancy. Such control could be offered by extending SDR with a control plane (complementing the network control plane in SDN, and including also methods for spectrum sensing). Unfortunately evolutions on SDN, on one hand, and SDR and CR, on the other hand, have so far been happening in different research communities, while a multidisciplinary approach bringing together experts from multiple disciplines (PHY layer, FPGA programming, network) is required to realize the integrated SDN-SDR vision. In parallel, mmWave SDR technology is today not yet fully available, as this technology really pushes the limits of the real-time flexible baseband design.

II. ORCA VISION

The overall ORCA vision is to drive end-to-end wireless network innovation by bridging real-time SDR and SDN exploiting maximum flexibility at radio level, medium access level and network level, to meet very diverse application requirements.

This vision is illustrated in Fig 1 and is further explained step-by-step using factory-of-the-future as the driving scenario. The manufacturing industry is one of the most demanding verticals with respect to ultra-low latencies, ultra-high reliabilities, ultra-high data rates, ultra-high availability, reliable indoor coverage in harsh environments (with a lot of metal structures) as well as energy-efficient and ultra-low communication costs for produced, connected goods. At the top of figure (beige colour) different traffic classes can be observed corresponding to different application requirements. For the manufacturing scenario, a (non-exhaustive) list of traffic classes (TCs), can be identified (inspired by [1] and [2]):

TC1: time-critical sensor/actuator control loop: bidirectional communication, low data rate (order kbps), stringent timing requirements (below 1 ms cycle time, order 100 µs response time, below 1 µs jitter), ultra- high reliability (99.9999999 %), indoor, very short range (order 10 m). Examples: motion control in printing machines, textile weaving machines, paper mills.

TC2: time-critical vision-controlled processes: bidirectional asymmetric communication ultra-high data rate (up to 10 Gbps), low latency (below 0.5 ms), high reliability (99.99999 %), indoor, short range (10-100 m). Example: vision---controlled robot arms, vision---controlled quality inspection, wearables and augmented reality on the shop floor.

TC3: low-latency continuous medium throughput: point-to-point and point-to-multipoint, moderate data rate (order 10-100 kbps), low latency and jitter (both below 10 ms), ubiquitous coverage and high availability (indoor + onsite outdoor), mobility support, large autonomy. Example: voice communication between workers with headset in manufacturing hall.

TC4: correlated data capturing: moderate data rates (kbps up to 100 Mbps), moderate latency (10-100 ms), ultra-high time synchronisation accuracy (below 100 ns), and moderate reliability (99.999 %), ubiquitous indoor coverage. Example: capturing of time-correlated sensor data on the shop floor to facilitate virtualized design processes that integrate simulator data with real-life data sensed during production.

TC5: non time-critical in-factory communication: moderate data rates (kbps up to 100 Mbps), latency in the order of 100 ms (limited by human response times), moderate reliability (99.999 %) ubiquitous coverage and high availability (indoor + onsite outdoor), mobility support. Examples: interactions between humans and machines or robots, localization of assets and goods.

TC6: bursty traffic: non-time critical (very large latencies allowed), large data volumes (MB up to 100 GB). Examples: sporadic software/firmware updates of machines, temporary reconfiguration of machines.

TC7: best effort: low priority, no firm guarantees on data rate or latency, minimal shared capacity, ubiquitous coverage (indoor-outdoor). Example: typical Internet application (email, surfing the web).

Current technologies lack capabilities with respect to the wireless performance and managing heterogeneity of devices, technologies and application (traffic) demands. A flexible and seamless connectivity across different radio access technologies (RATs) will be required in order to adapt instantaneously variable capacity and mobility needs to changing environments and application needs. A first approach to deal with such very diverse traffic demands is applying SDN techniques: instead of operating one physical network infrastructure for dealing with the different traffic classes applying complex traffic engineering or QoS scheduling mechanisms, the network infrastructure can be virtualized into separate independent network infrastructures, applying the most appropriate protocols and resource sharing mechanisms for dealing with a specific traffic class. This approach is called network slicing or vertical slicing. This is illustrated by the vertical, coloured pipes in Figure 1, each pipe representing a single network slice architected and optimized for the specific requirements for the applications supported by its traffic class. For the manufacturing scenario described above, this results in 7 different pipes. The main focus of SDN today is on wired networks (Ethernet, optical transport networks) and on layer 3. ORCA will offer a wireless SDN, by extending the current SDN vertical slicing capabilities with lower layer wireless capabilities.

To this end, the vertical pipes (corresponding to different traffic classes) need to be mapped onto the radio resource grid (bottom of Fig 1), hereby maximally exploiting the radio degrees of freedom like time, frequency and space. Please note that the space dimension will allow the reuse of spectrum and time resources through space division multiple access (not shown in Fig 1). The radio resource grid corresponds to the overall capacity of the radio infrastructure. Each block in the radio resource grid represents a chunk of radio resources consuming a certain part of the airtime, spectrum and space (controlled by the power setting for omnidirectional antenna or by directional beam in 3D MIMO case) with a certain PHY configuration (modulation and coding scheme) providing a certain dynamic capacity (in terms of data payload it can carry). This capacity is dynamic, as it changes over time due to changes in the wireless environment (requiring adaptations to the PHY). The mechanism of mapping vertical pipes to radio resource blocks is called radio slicing. It is responsible for the dynamic allocation of available resource blocks in the radio resource grid over the different traffic classes.

The focus in ORCA is on wireless functionalities that are needed to extend current SDN concepts. ORCA has no intention to develop new network-level SDN paradigms, but will align with other SDN-oriented initiatives (like the parallel large collaborative FIRE+ project for large-scale experimentation for service delivery networks, based on heterogeneous and cooperative networks integrated through SDN/NFV techniques) to ensure that ORCA developments are compliant with common SDN mechanisms.

III. ORCA METHODOLOGY

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, as is introduced in SDN networks [3] [4] and illustrated in Fig 2.

ORCA will extend SDN with the software-defined control of advanced radio capabilities. ‘Radio’ refers to RF (the physical layer functionality in the analog RF domain), the PHY processing (the physical layer functionality in the digital domain) and medium access (link layer functionality for sharing the wireless medium). The different planes and their main functionalities at the different levels are described hereafter. In ORCA we will primarily focus on the radio level functionality, and align SDR developments with SDN developments in parallel in other initiatives, such as the ONF (the Open Networking Foundation [5]) or projects like SPARC [6], OFELIA [7] and UNIFY [8].

A. Data plane

Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable. The data plane consists of the network data plane (the software defined network data plane that operates as a network forwarding infrastructure) and the radio data plane that operates at the RF level, signal processing level, and a medium access level). The radio data plane consist of:

- **medium access data plane:** enabling implementation of various channel access schemas and performs MAC layer related framing
- **PHY processing data plane** performing digital baseband processing functionalities through the usage of processing chains which are formed from processing units (usually signal processing accelerators on FPGA)

- **RF data plane** performing analog radio frequency signal processing.

B. *Control plane*

The SDN control plane offers a common interface for developing radio or networking applications. This interface, also called northbound interface (or NB) abstracts the low-level instruction sets used by the southbound interface (SB) towards the application plane. While the northbound interface is independent from implementations in the data plane, the southbound interface depends on specific implementations on specific HW platforms. In ORCA the control plane will extend the SDN control plane with interfaces for advanced radio control. The radio control plane consists of:

- **medium access control plane**: control interface for runtime adaptation of MAC schemes, either by adjusting MAC parameters or by switching between MAC protocols.
- **PHY processing control plane**: control interface for runtime adaptation of the transceiver chain through (with increasing level of complexity)
- **RF control plane**: control interface for adapting the RF operation of the radio, such as the frequency of the local oscillator, bandwidth of analog filter, target/parameters of receiver AGC or transmitter power control, antenna steering, etc.

C. *Application plane*

The application plane is comprised of the control logic, called radio/network application, responsible for the radio and network control functionality. While traditional SDN is mainly focusing on reconfiguration of the forwarding behaviour of the network, ORCA will also focus on the reconfiguration of the radio functionality (medium access control, PHY processing and RF) to account for the dynamics of the wireless environment. In contrast to wired networks, where a stable link with fixed capacity is offered, wireless links are unstable and have a dynamic capacity, which requires a more advanced monitoring and control. ORCA will develop intelligent radio/network control functionality and applications to deal with compelling wireless scenarios like network virtualization and multi-RAT support. Intelligent radio/network applications can benefit from the control programs that run on top of the WiSHFUL [9] UPIs, and intelligence algorithms that are developed in WiSHFUL and eWINE [10]. We further notice that individual applications could control both network and radio parameters via separate radio and network interfaces that exist in the control plane.

D. *Management plane*

The management plane enables configuration of individual components across the other planes. This involves the configuration of application-specific parameters (such as SLAs), the configuration of communication ports in between the other planes (e.g. which port to use between data and control plane) or setting up and upgrading individual devices. In ORCA we will focus on radio management functionality in the data plane for updating and upgrading radio functionality, more specifically:

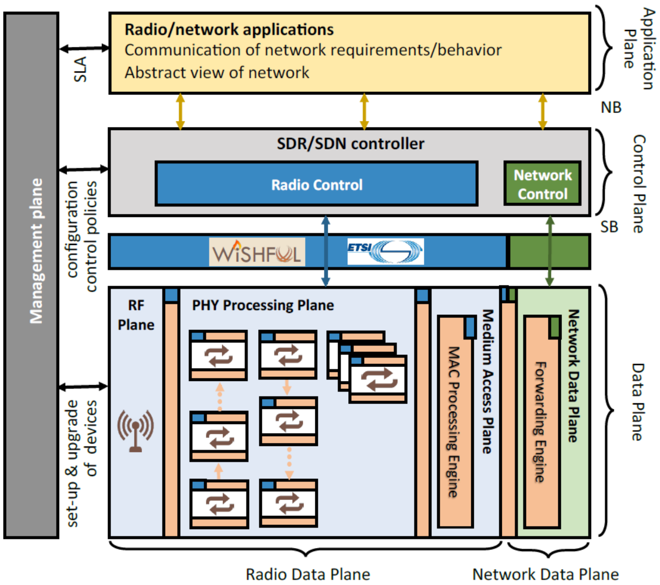

Fig. 2 ORCA approach: realizing an integrated SDR-SDN architecture

- MAC level code updates or upgrades with new or improved functionality.
- PHY level code updates or upgrades with new or improved functionality. Different approaches will be considered (with increasing complexity): (i) update/upgrade of a full transceiver chain by software/hardware reprogramming (ii) update/upgrade of one or multiple processing units on the transceiver chain by partial code updates as well as RF driver updates.

We consider two options for the implementation of radio control and radio management plane:

- over the testbed control backbone: in this case (re)configurations and code updates are only possible when the SDR hardware is connected to the testbed control backbone
- over the air: in this case, configurations and code updates are part of the solution under test and hence updates are also possible when the SDR hardware is disconnected from the testbed. Here, we also have to provide code dissemination strategies for downloading code from a code repository and strategies for synchronized activation of the code after installation, including verification and rollback mechanisms in case the code is not properly installed or activated on all involved devices. ORCA will build a repository for storing code modules (software or hardware).

IV. ORCA SHOW CASES

The goal of this section is to introduce the relevant showcases to promote ORCA capabilities. The showcases to be presented cover different aspects of CR, 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. Augmented reality and virtual reality will be key to enable a smooth cooperation of robots and humans in the factory of the future. Achieving such very high throughput in dense networks, challenging environments such a production floor, for static and mobile users, will require a tight co-design of the wireless link and mobile network ensuring the service is delivered. This first ORCA showcase will illustrate how a tight co-design of link and network can be achieved using the ORCA tools, offering solutions first for static robots and later for mobile robots.

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. This showcase can be used by external partners to compare different PHY and MAC layer solutions to control the robots in real-time, but also to compare remote control via centralized cloud processing with autonomous local control concepts. Besides wireless link experiments, there are also localization experiments possible. For example, exploring if distributed access points can be used to determine the position of a mobile device.

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. The instantiation of customized networks optimized to a specific demand is enabled by the flexibility in the physical layer and by the use of virtualization. This showcase aims to demonstrate the concept of vertical slicing, as illustrated in Section II, 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 very dense network slices on a single SDR 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. 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. One 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. Within the ORCA project the interworking of a 3GPP LTE system together with a new mmWave RAT as well as 802.11 is possible. The flexibility of the platform enables researchers to investigate how the 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.

V. CONCLUSIONS

In conclusion, the ORCA project brings together multi-disciplinary expertise to achieve autonomous and intelligent end-to-end user and networking control, and the optimized usage of spectrum, hardware and energy resources, resulting multiple heterogeneous network slices sharing the same underlying infrastructure and spectrum.

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