Space Division Multiplexing 5G Fronthaul with Analog and Digital Radio-over-Fiber and Optical Beamforming – *the blueSPACE Concept*

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Short summary

This paper presents the concept of the blueSPACE project. The blueSPACE project is one of the 21 second phase 5G-PPP initiative European H2020 projects focusing on delivering solutions, architectures, technologies and standards for the ubiquitous next generation communication infrastructures. This concept paper presents the blueSPACE proposition for the use of spatial division multiplexing for 5G fronthauling, the use of optical beamforming from Ka-band wireless signals, the incorporation of power-over-fiber distribution and the integration into a flexible SDN/NFV environment. Also, the chosen use cases and a global description of the planned demonstrations are presented.

1 Introduction

For ICT systems to cope with the rapidly increasing growth of data transmission rates, there is a need for a flexible, scalable, and future-proof solution to seamlessly interface the wireless and photonic segments of communication networks. In addition, emerging paradigms such as 5G communications, the internet of things (IoT), vehicle-to-vehicle and vehicle-to-infrastructure (V2V and V2X) communications, wireless body and personal area networks (WB/PANs), and high-resolution sensing are expected to push this pressure even further. The requirements demanded by most of these scenarios calls for novel technology developments in both the physical layer and the network architectures. For instance, 5G wireless communications targets a 1000-fold increase in capacity, connectivity for over 1 billion users, strict latency control, and network software programming. Achieving these targets with the existing technology is impossible. Therefore, a wide range of new technologies must be developed, starting from the radio interface, through the fronthaul-, backhaul- and core networks, to the processing and management software and underlying IT infrastructure. A significant upgrade is required to support the 5G new radio (NR) standards and upcoming features like radio frequency (RF) beamforming and -steering. Indeed, deploying millimeter wave (mm-wave) NR, small cells and massive multiple input multiple output (MIMO) transmission will create such a big amount of real-time traffic that it would require an unaffordable fronthaul network, unless a scalable and cost-effective solution is developed. This is the focus of blueSPACE.

blueSPACE targets a disruptive yet pragmatic approach for the deployment of scalable, reconfigurable and future-proof fronthaul solutions for 5G communications, offering unrivalled characteristics that include:

a. increased bandwidth provisioning by naturally enabling and supporting MIMO transmission starting/ending in the fiber medium, and by enabling space diversity in the RF domain by supporting RF beam steering in the photonic domain,

b. a compact infrastructure that is reconfigurable by means of software defined networking (SDN) and network function virtualization (NFV) paradigms, and

c. the possibility of providing full integration with other existing approaches for the implementation of access networks, such as passive optical networks (PONs).

The core concept of blueSPACE is to exploit the added value of optical space division multiplexing (SDM) in the radio access network (RAN) with an efficient optical beamforming interface for wireless transmission in the pragmatic 24.25 GHz to 27.5 GHz band. The developed solutions will integrate seamlessly into existing and next generation optical access network infrastructures, while fully supporting SDN and NFV.

2 BlueSPACE SDM Network Architecture

The centralized RAN (C-RAN) concept relies heavily on centralization and virtualization of baseband processing units (BBUs) and thus places a heavy burden on the fronthaul network connecting the latter to the remote radio units (RRUs). CPRI, the commonly employed standard for optical fronthaul, aggravates this problem as it requires high transmission rates even for low RF bandwidths, and thus cannot scale to large RF bandwidths or dense deployments. In blueSPACE, we propose to adopt the space dimension in the physical layer, as shown in Figure 1, to extremely increase the capacity of 5G fronthaul at a reduced cost. The purpose is:

a. to introduce the concept and benefits of space division multiplexing in both networking and the support of new technologies for 5G front-hauling,

b. to build upon existing infrastructures (rather than defining new ones) and make use of bundles of single mode fibers (SMFs) that are typically available in most of the optical distribution network (ODN), not least as a transition towards multi-core fiber (MCF) based ODNs,

c. to consider MCF and develop novel infrastructures for future-proof capacity expansion solutions using the same ducts, and

d. scalable solutions to remotely supply power-over-fiber (PoF) for massive small cell deployments.

With the use of analog RoF and SDM-based fronthauling, blueSPACE is capable of supporting the massive deployment of RRUs, while providing different degrees of centralized processing, allowing the development of more advanced virtualization solutions for the access segment. In this framework, NFV and SDN control can be adopted for improved resource sharing and performance while supporting virtualization of the SDM

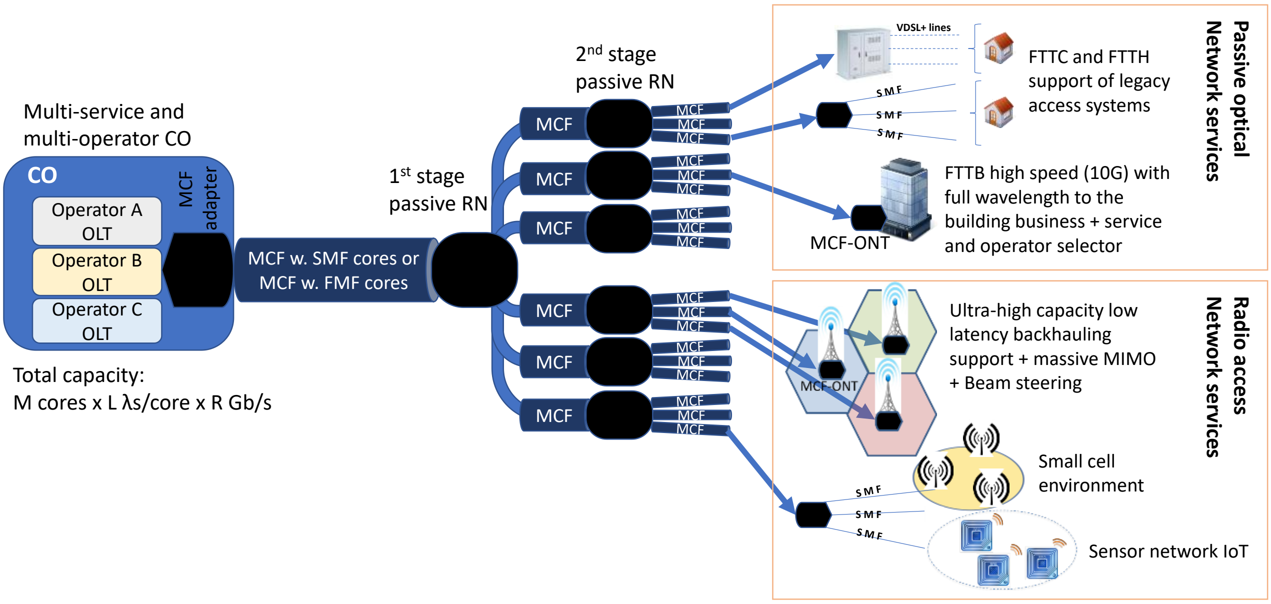

Figure 1: blueSPACE network architecture vision based on SDM-enabled transport technology and supported services.
MCF: multi-core fiber, SMF: single mode fiber, RN: remote node, CO: central office, FTTx: fiber to the: B: building, C: curb, H: home.

fronthaul infrastructure for multi-tenant environments [1], [2]. blueSPACE will develop the associated SDN/NFV control framework.

Figure 1 provides an abstract vision of blueSPACE's proposed SDM-enabled 5G front-haul architecture comprising:

i. a multi-service multi-operator central office (CO) with SDM capabilities,

ii. the fiber infrastructure based on MCFs with different numbers of cores,

iii. two stages of passive remote nodes (RNs), and

iv. different end services supported by the centralized CO, including PON and RAN services.

The CO delivers its data signals to the optical distribution network to provide connectivity to the different cell sites. This optical distribution network is expected to be mainly passive, featuring low operational expenditure (OPEX) and limited capital expenditures (CAPEX). The CO will be equipped with spatially integrated SDM transceivers which will be centrally controlled by an SDN control plane specifically developed in blueSPACE to support the capabilities offered by the spatial dimension.

The integrated transceivers in the CO are connected to a high core-count MCF through a specific interface which will be developed as one of the contributions of blueSPACE. The high core-count MCF will be distributed across lower or similar core-count MCFs after passing through two stages of passive RNs. By considering such a design, the highest level of spatial integration can be realized in the CO, resulting in further reduced cost and power consumption. The transmitted signals will be distributed in different consecutive stages to cover a wider geographical area as well as enabling alternative end-services including PON, DRoF, ARoF, etc. As the fiber infrastructure gets closer to the end nodes, the core count decreases, enabling the blueSPACE proposed SDM solution to, for instance, target the small/femto-cell deployment. Additionally, selected core-count MCFs are compatible with optical beamforming capabilities at the CO or the RRU, for which the number of cores is determined by the number of antenna elements in the array or the number of supported beams respectively. Besides, MCFs will be demultiplexed to the SMF level in some cases due to the requirement of lower capacity and the necessity of deploying very low-cost transceivers. The passive RNs which are placed in the ODN will be specifically designed and developed in blueSPACE to support interfacing between various required MCF core-counts. The SDM-enabled SDN control plane will be designed to efficiently manage the resources (core/mode/wavelengths/optical carriers). On top, NFV will be also developed to efficiently utilize all available resources.

3 5G Fronthaul over Fiber Transport: ARoF and DRoF

This section describes 5G fronthaul concept and the design of the central office infrastructure, i.e., the electrical switching and interconnection architecture between the BBU pool or ARoF BBUs and the DRoF and ARoF optical transceivers.

3.1 blueSPACE Analog Radio-over-Fiber Concept

The blueSPACE analog radio-over-fiber (ARoF) concept focuses on the intermediate frequency-over-fiber (IFoF) delivery of the orthogonal frequency division multiplexing (OFDM) modulated 5G NR signals, optical beam-forming and photonic up-conversion to the mm-wave (26 GHz) band at the RRUs, as depicted in Figure 2. The BBUs generate the data stream according to digital data originated from the backhaul and physical layer control signals according to the 5G NR radio interface technology (RIT) formats. The outputs of the BBUs are fed to the IQ modulators and IF up-converters. The modulated IF signals are amplified and drive the electro-optical modulators. The optical signals exiting the modulators are fed to the optical beamforming network (OBFN) and then driven to the SDM multiplexing/demultiplexing interface towards the MCF.

At the cell site, the modulated optical signals beat with the optical local oscillator (LO) on high-bandwidth photodiodes to produce the mm-wave electrical signal. In this configuration, the optical signals travelling in the MCF carry the phase information required to perform the RF beamforming at the RRU antenna. So, the relative phase alignment between the MCF cores must be maintained. This is a hard requirement to meet over multiple kilometers of optical transport, unless MCF with heterogeneous cores and thus minimal propagation delay differences is employed. The monitoring of such delay differences (skew) between fiber cores is investigated in blueSPACE and systems for latency measurement are developed [3], [4].

3.2 blueSPACE Digital Radio-over-Fiber Concept

The blueSPACE concept for DRoF is shown in Figure 3. It takes advantage of the wavelength and space dimensions. A central office is attached to an optical metro/core network to provide connectivity to the network edge. At the CO, a pool of BBUs delivers the traffic to the corresponding bandwidth/bitrate variable transceivers (BVTs). These transceivers are suitably configured to provide certain capacity for a desired

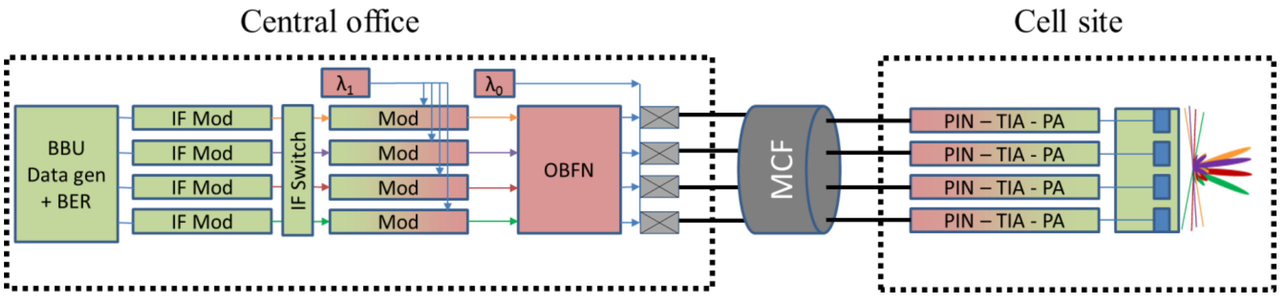

Figure 2: blueSPACE analog radio-over-fiber (ARoF) concept with optical beamforming. BBU: base band processing unit, BER: bit error rate tester, PIN: photodiode type p-i-n. TIA: transimpedance amplifier, PA: power amplifier, IF: intermediate frequency, IF Mod: intermediate frequency modulation, Mod: optical modulator, MCF: multicore fiber, λ_1: optical carrier for IF modulation, λ_0: injected optical local oscillator.

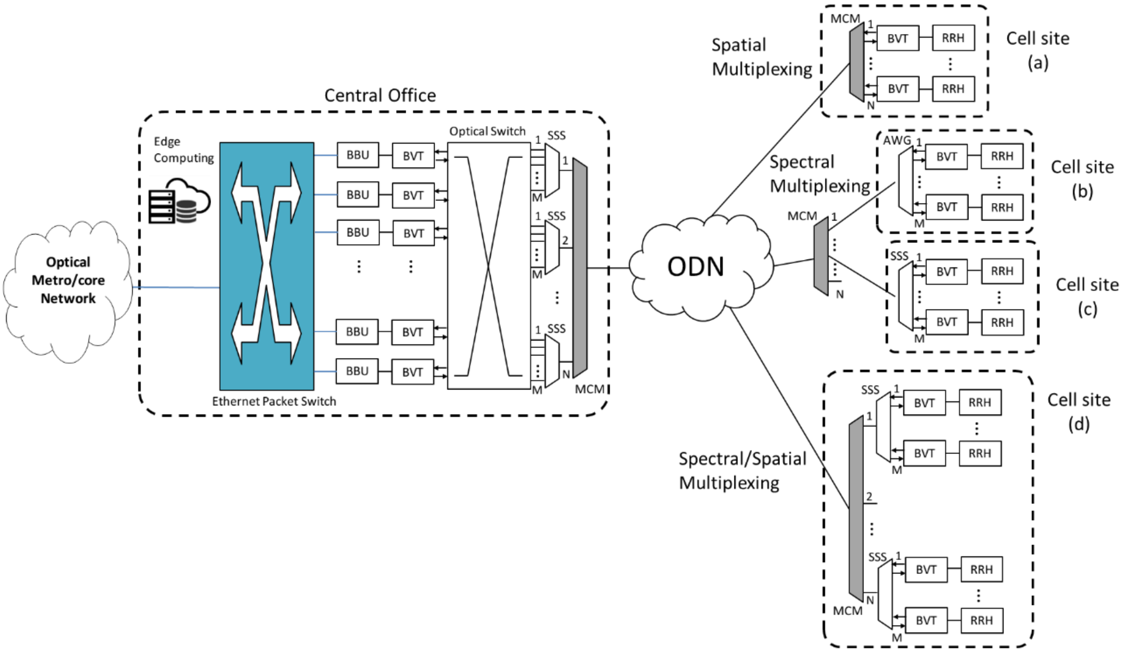

Figure 3: blueSPACE concept for digital radio over fiber transport.
BBU: baseband unit, BVT: bandwidth/bitrate variable transmitters, SSS: spectrum selective switch, MCM: multi-core multiplexer, AWG: arrayed waveguide grating, RRH: remote radio head, ODN: optical distribution network.

wavelength/channel. The number of BVTs can be different from the number of BBUs served, if they are interfaced by a convenient analog switch. The BVTs are transceivers able to vary its capacity and/or bandwidth according to the instructions of the control plane. Hence, the BVTs can be remotely configured by the control plane for an optimal management of the network resources. In addition to the bitrate variability that can cope with a dynamic traffic variation (e.g., daily traffic variation), the BVTs also feature other benefits such as the capability to maximize its capacity for a given connection. The inputs/outputs of each BVT are connected to an optical switch in order perform the appropriate connections to each of the spectrum selective switches (SSSs), which perform the wavelength division multiplexing/de-multiplexing of different signals into arbitrary portions of the spectrum according to the control plane indications. The main outputs of the SSSs are connected to the spatial multiplexers, which are the fan-in/-out devices for the MCFs.

As for the cell sites, different options are envisioned. A first cell site option, labeled (a) in Figure 3, is the so-called spatially multiplexed site. There, the BVTs are tuned to use the very same wavelength while using different cores either for scaling up the capacity or for implementing a dual-core duplex. Therefore, a simplification of the BVT can be foreseen, by multiplexing on different fiber cores using the same wavelength. Hence, space and spectrum resources can be managed by a centralized SDN controller to provision the different services, possibly including residential access and/or other services that could require a direct interface with the metro/aggregation segment. All the systems and subsystems belonging to the central office and, especially, the BVTs can be programmed by means of the corresponding SDN agents, allowing an automated channel establishment between the central office and the cell sites in a 2D space (WDM + SDM).

The cell site options labeled (b) and (c) in Figure 3 correspond to a spectrally multiplexed site. In that case, a single core or fiber is used with wavelength division multiplexing exclusively. A straightforward approach can be to employ passive devices – for example an arrayed waveguide grating (AWG) as in cell site (b) – to perform the wavelength multiplexing resulting in a low-cost solution. Also, active devices such as SSSs, as shown in cell site (c), can be employed, trading cost against flexibility. It should be noted that here a dual wavelength duplex is envisioned.

Finally, a generic option is depicted in cell site (d). There both spatial and/or wavelength multiplexing are used to exploit all the features illustrate one of the main benefits of the blueSPACE DRoF proposed architecture: it is highly reconfigurable and very flexible. In fact, the CO and the different cell sites are expected to host their corresponding SDN control agent to configure the main parameters for the efficient control of the fronthaul traffic over the optical network. In turn, each SDN control agent interacts with the control plane infrastructure, which oversees the overall network management. Therefore, the programmability of the different elements composing the CO and the cell sites is of key importance.

3.3 blueSPACE Power-over-Fiber Concept

This section presents the blueSPACE concept of a power distribution system for remote powering of network terminals under specific conditions. The energy autonomy of wireless devices is a key issue to get a self-sufficient wireless network. Energy harvesting is a potential solution to supply wireless systems with ambient or ‘free’ energy from sources such as solar, vibration, and thermoelectricity, however the power levels available from harvesting sources are still low.

Power-over-fiber (PoF), or the delivery of power through an optical fiber, may help in providing the required energy, isolated or in combination with electrical power cables, batteries or energy harvesting devices. The use of PoF is advantageous in situations in which sparks or shorts may be a fatal problem, and in situations where immunity to electromagnetic and RF interference is required. Moreover, blueSPACE has proposed and investigated the novel concept of PoF pooling [5], which can make PoF scalable to outdoor small cell deployments, especially those that follow the so-called phantom-cell approach. This optical power delivery means a permanent network connectivity between CO or the network node where the high-power lasers (HPLD) for PoF may be placed, and RRU, even in the case of power failures or disasters, providing true 5G availability for critical services. An initial blueSPACE proposal describing the PoF system that can remotely be controlled on demand is depicted in Figure 4.

A pool of high power lasers for power over fiber (HPLDs-PoF) at λ_1 is shared between the different cores of an MCF, addressing the different RRUs. MUX and DMUX devices are used for combining data, power and control channels. The fan-in (FI) and fan-out (FO) splits the MCF cores into SMFs. A hardware energy management system (HEM) controls the energy delivered to each RRU. Depending on the power demand and distance of optical power delivery to be covered, SDM with fiber bundles will also be considered in blueSPACE, using PoF prototypes as those described in [6].

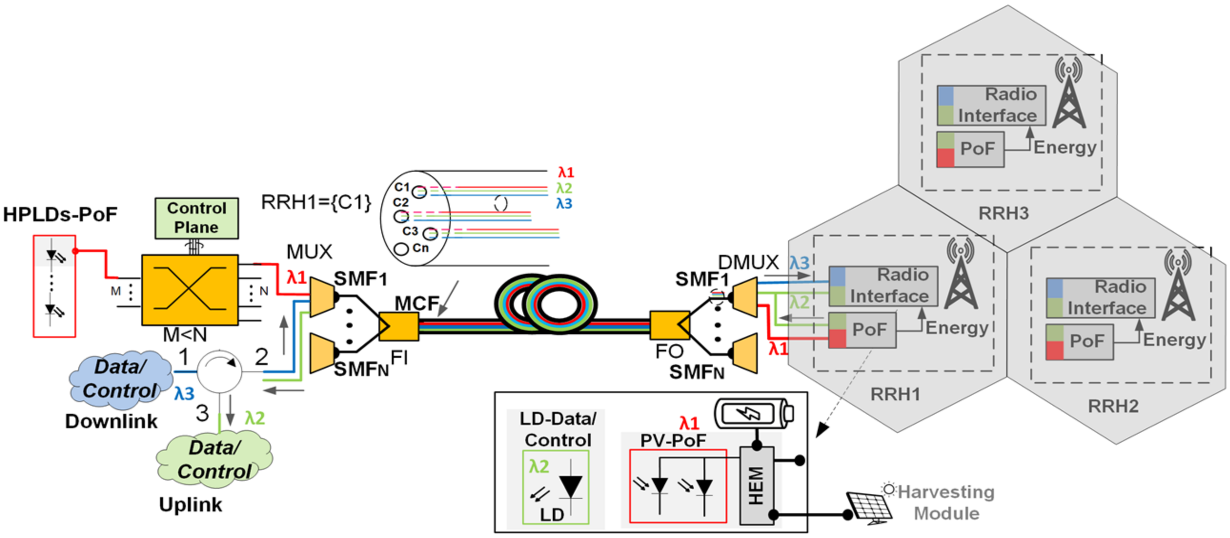

Figure 4: SDM 5G fronthaul with PoF from CO to small cells.
λ_1: power, λ_2: data, λ_3: control, PoF: power-over-fiber, HPLD: high power laser diodes, RRH: remote radio head, SMF: single-mode fiber, MCF: multi-core fiber, FO/FI: fan-in/fan-out, (D)MUX: (de-)multiplexer, PV: photo-voltaic, HEM: hardware energy manager.

4 Control Plane

The blueSPACE NFV MANO architecture is based on three main building blocks, the transport SDN controller, the NFV service platform and edge computing controller (VIM), and the network slice manager, as shown in Figure 5. Regarding the control plane architecture, blueSPACE adopts and further extends the NFV MANO architecture. This offers the required compatibility with existing interfacing solutions while it also allows the development of important extensions that are determined mainly by the SDM/WDM physical network infrastructure and the deployed technologies.

Key design challenges to be considered are: the support of multi-tenancy (i.e., slicing) with spatial allocation features, the extension of the SDN controller for the envisioned SDM/WDM-enabled fronthaul technologies, the management of physical network functions in addition to virtualized functions and the use of dynamic resource allocation algorithms with multiple optimization criteria. The architecture should consider a network slicing manager and NFV orchestrator at the top, which interfaces with the network management and services and further implements the resource allocation algorithms. The hierarchical transport SDN controller (WIM), the edge computing controller (VIM), and the virtual and physical network function (VNF and PNF) managers are directly attached to the orchestrator and are responsible respectively for the management of: connectivity services in the SDM/WDM-enabled fronthaul, the virtual computing, networking and storage resources, the virtualized functions, and the physical layer functions. Finally, the node SDN agents at the lower part of the architecture, provide the interfacing with the SDM/WDM system controllers and network topology services.

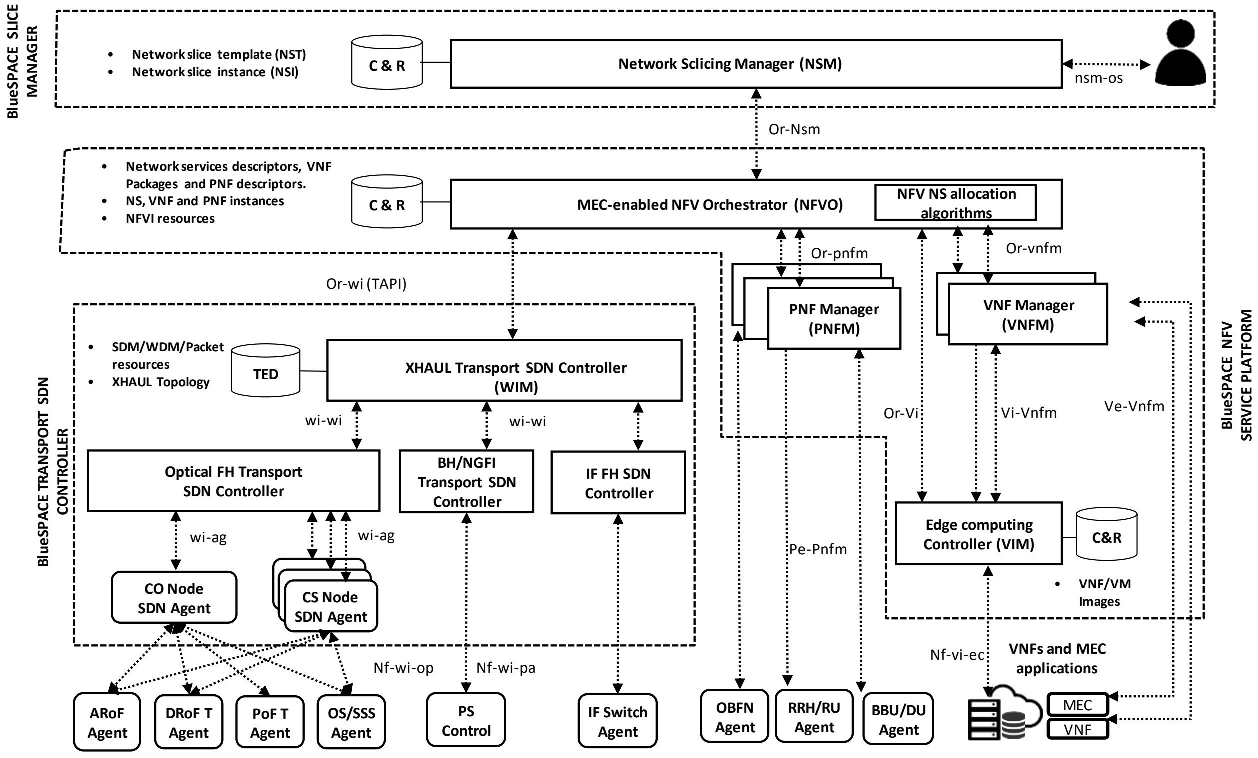

Figure 5: blueSPACE NFV MANO high-level functional blocks and interfaces.

5 BlueSPACE 5G Use Cases and Demonstrations

5.1 Use Cases Identified for blueSPACE

Four use cases (UC) have been defined for showcasing the blueSPACE benefits. These include two use cases with direct impact due to high connectivity demands and two use cases on emerging 5G fields in which the blueSPACE technology could have a significant impact. The two main use cases are:

UC1 ‘*Dense Urban*’: addressing the provisioning of enhanced mobile broadband (eMBB) services to a large number of concentrated users in stadiums, concerts, conferences, squares, etc.,

UC2 ‘*Smart Office*’: addressing the provisioning of ultra-high data-rate connectivity to a small number of users in an office environment or designated hotspot areas.

The two forward looking use cases are:

UC3 ‘*Mobile Broadband in Vehicles*’: targeting mainly public transport and aggregated traffic by many users with shared mobility,

UC4 ‘*Massive Machine Type Communications in Industry 4.0*’: targeting mMTC scenarios in which the need for high bandwidth connectivity to a large number of closely-located sensors and quality inspection devices is expected.

5.2 blueSPACE Demonstrations in the Eindhoven 5G Brainport Testbed

The Eindhoven 5G Brainport platform allows validation and exploitation of 5G application scenarios in a highly dynamic and integrated testbed. Figure 6 shows part of the Eindhoven 5G Brainport platform located on the TU/e campus. The 5G Brainport platform is based on the C-RAN concept that accounts for the fronthaul segment [7] between the CO and RRU with the radio interfaces to the end user equipment. The testbed platform is built on fiber optics, supporting both digital and analog radio-over-fiber fronthaul [8], [9], and focusses on low latency, high data-rate applications requiring mm-wave signals [10]. To achieve the data-rate goals, 5G networks will employ novel MIMO systems and eventually use more bandwidth at the mm-wave frequencies. This innovative deployment demands antenna array systems with many active antenna elements operating fully coherently. The use of a large number of antenna elements helps to focus the

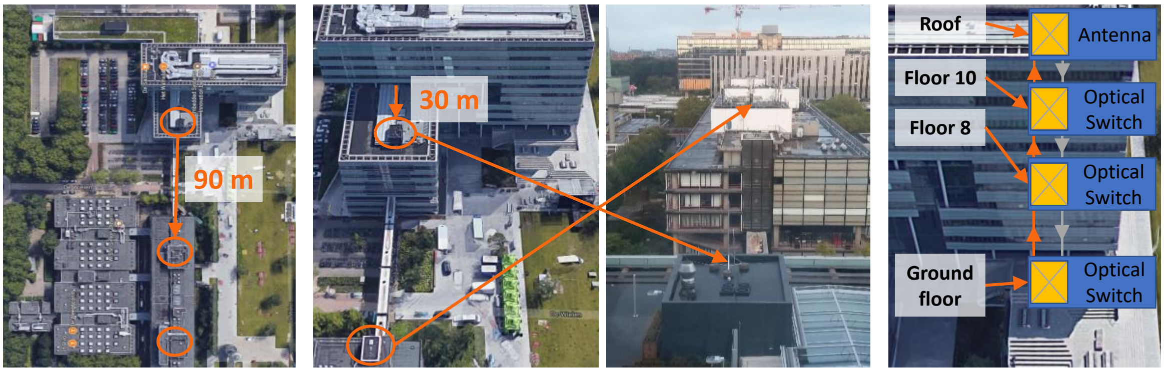

Figure 6: Inter-building and intra-building communication on the TU/e campus, part of the 5G Brainport testbed.

In this set-up, blueSPACE envisions to test use case UC1, addressing the provisioning of broadband services to a large number of concentrated users in stadiums, concerts, conferences, city squares, etc.

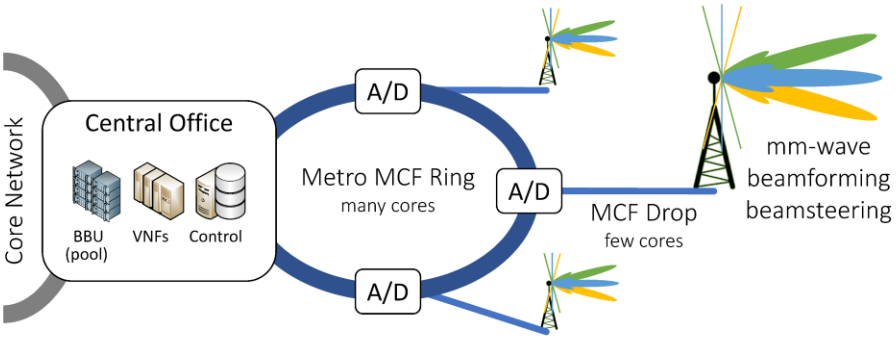

Figure 7: The Eindhoven 5G testbed based on mm-wave and optical space division multiplexing technologies in support of 5G-PPP project blueSPACE.
A/D: add/drop node, MCF: multi-core fiber, mm-wave: millimeter wave, BBU: baseband unit, VNF: virtualized network function.

transmission and reception of signal energy into ever-smaller regions of space, which, brings improvements in throughput and energy efficiency.

Figure 7 illustrates part of the concept currently under development in the 5G Brainport testbed platform. It is worth mentioning that with the use of SDM and MCF, the testbed achieves fronthaul capacities sufficient to provide the target 5G peak user and cell data rates, while enabling the use of optical beamforming techniques, simplifying the RRU architecture while maintaining advanced RF beam-shaping and -steering capabilities. In turn, the radio interface, which combines mm-wave carriers as well as beamforming and -steering capabilities, maximizes the capacity and ensures signal quality regardless of user location and motion. The RF chains at the radio interface are significantly simplified as the beamforming is performed in the optical domain, which reduces power consumption and complexity.

In addition, the testbed supports both enhanced mobile broadband (eMBB) and URLLC services through the combination of improved dynamicity of the optical and radio techniques and intelligent and dynamic management of 5G applications. Moreover, the 5G platform testbed is connected to the Dutch national and European communication networks rendering not only functionality on its own, but also allowing it to be part of a distributed, large scale test platform that ensures usability beyond the scope of current projects. Hence, the 5G Brainport platform paves the way beyond the boundaries of current optical technology by exploring optical infrastructure elements, like ROADM, flexible transponders and transceivers, etc., in a disaggregated multi-vendor environment.

Given the involvement in a number of leading 5G-PPP phase 2 projects, the Eindhoven 5G Brainport experimental platform facilities will be used in the context of blueSPACE, to initially carry out test for mm-wave links in the 26 GHz band for high capacity access and provisioning to dense user areas. In a later stage, other verticals use cases include:

a. an intelligent transport system and autonomous driving application, where eMBB and URLLC communication needs are combined with V2X communication trials,

b. a cooperative autonomous robot soccer game, equipping TU/e’s RoboCup winning team with a 5G communication framework and upgrading the cooperative traffic exchange between soccer robots that currently operate at 2.5 Mb/s, significantly boosting the environment perception and modelling of robotic players, and

c. a cooperative autonomous drone use-case, where a number of drones can have their sensory data offloaded to the cloud, subsequently allowing cloud-controlled cooperation, which can eventually improve synchronization among drones.

These use cases target the following 5G KPIs: ultra-low latency down to 1 ms with only10 μs data plane jitter, 99.99 % reliability and availability, and finally broadband mobile services with high mobility support for speeds over 200 km/h.

6 Conclusions

This paper presented the concept, technologies and network architectures for 5G fronthaul addressed in blueSPACE. The proposed concept is a necessary step towards a completely overhauled radio access network architecture, in line with the demanding 5G KPIs and compatible with the current phase of 5G developments, where scalability, manageability, and flexibility are also targeted as major network requirements.

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List of abbreviations and acronyms

Abbreviation	**Meaning**
5G	5th Generation Mobile Communications
5G NR	5G New Radio
5G-PPP	5G Infrastructure Public Private Partnership
ARoF	Analog Radio-over-Fiber
BBU	Baseband Unit
BVT	Bandwidth Variable Transceiver
C-RAN	Centralized Radio Access Network
CAPEX	Capital Expenditure
CO	Central Office
CPRI	Common Public Radio Interface
DMUX	De-Multiplexer
DRoF	Digital Radio-over-Fiber
eCPRI	Enhanced Common Public Radio Interface
eMBB	Enhanced Mobile Broadband (5G Traffic Class)
FI	Fan-In
FO	Fan-Out
H2020	Horizon 2020 (European Union research funding)
HEM	Hardware Energy Manager
HPLD	High-Power Laser Diode
IF	Intermediate Frequency
IoT	Internet of Things
IQ	In-Phase/Quadrature
KPI	Key Performance Indicator
LO	Local Oscillator
MCF	Multi-Core Fiber
MANO	Management and Orchestration
MIMO	Multiple-Input Multiple-Output
mm-wave	Millimeter Wave
mMTC	Massive Machine Type Communications (5G Traffic Type)
MUX	Multiplexer
NFV	Network Function Virtualization
OBFN	Optical Beamforming Network
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
OPEX	Operational expenditure
PNF	Physical Network Function

Abbreviation	Meaning
PoF	Power-over-Fiber
PON	Passive Optical Network
RAN	Radio Access Network
RF	Radio Frequency
RIT	Radio Interface Technology
RN	Remote Node
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RoF	Radio-over-Fiber
RRU	Remote Radio Unit
SDM	Space Division Multiplexing
SDN	Software Defined Networking
SMF	Single-Mode Fiber
SSS	Spectrum Selective Switch
TU/e	Eindhoven University of Technology
UC	Use Case
URLLC	Ultra-Reliable Low Latency Communications (5G Traffic Type)
V2V	Vehicle to Vehicle
V2X	Vehicle to X (X = infrastructure, vehicle, etc.)
VIM	Edge Computing Controller
VNF	Virtual Network Function
WBAN	Wireless Body Area Network
WDM	Wavelength Division Multiplexing
WIM	Xhaul Transport SDN Controller
WPAN	Wireless Personal Area Network