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The Optical Fiber and mmWave Wireless Convergence for Fronthaul 5G Networks

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Abstract—The most radical evolution in recent mobile communication technology is imminent in the coming years. The fronthaul network architecture is part of this evolution and is expected to support in a cost-effective manner dense deployment of infrastructure to provide increased bandwidth and ultra-low latency for 5th generation (5G) networks. The new fronthaul architecture called cloud radio access network (C-RAN) has been introduced over the last years to increasing scalability, manageability, and flexibility of mobile systems. In this context, this paper addresses the principal technology enablers of the C-RAN 5G fronthaul architecture, namely radio-over-fiber, ribbon optical fibers, wavelength-division multiplexing, and millimeter wave (mmWave) frequencies. The convergence of optical fiber networks and mmWave radio pave the way towards a truly efficient fronthaul infrastructure for 5G mobile communications with seamless connectivity for millions of devices and quality-of-service guarantees in terms of latency for the first time ever. We perceive a network scenario with seamless starting and ending interfaces by exploiting space diversity in both radio frequency and optical domains with efficient integrated photonics technology. Furthermore, we introduce the ongoing developments of the Eindhoven-based 5G Brainport testbed towards an open environment for validation and test of end-to-end emerging applications benefitting from the 5G key-performance indicators.

Keywords—5G; RoF; mmWave; WDM; PON; ribbon fiber; C-RAN; KPI; fronthaul

I. INTRODUCTION

The recent explosion in the deployment of optical fiber cabling in several countries is not solely due to fiber-to-the-premises solution-based demand, but it is actually due to the substantial increase in broadband cellular connectivity lead by thousands of bandwidth-hungry users, which is driving the cellular industry to upgrade from the long-term evolution technology to 5th generation (5G) mobile communication systems, and consequently installing new optical fiber infrastructure. Indeed, 5G networks are accelerating optical fiber links deployment that are being installed more than ever before and the tendency is to grow even further. Data-intensive wireless services based on mobile communication such as downloading a movie onto a mobile device or streaming video with next-wave content like, for example, augmented and virtual reality as well as 4K ultra high-definition, are driving the way towards massive deep fiber installations near the end-user to support 5G services. This new hybrid communication system based on optical fiber and wireless mobile technology has yielded a new concept of mobile fronthaul architecture.

The continuous advances in both technologies have led to new economically feasible solutions for 5G fronthaul infrastructure, where for the first time ever in modern advancements in mobile communication technology, 5G networks will additionally accommodate millions of wireless sensor connections for real time data analyses and support quality-of-service with ultra-low latency down to 1 ms [1].

Recently, besides this accentuating increase in fiber infrastructure deployment, new 5G small cells are being massively installed in urban areas, with a smaller coverage area when compared to classical cells, which increases even more the extension and amount of fiber to be used. Ribbon fibers can be one of the many possibilities to install in a cost-efficient manner such a large reach extent based-solution. Rollable fiber ribbons [2], a fiber-optic ribbon rolled into a tight cylinder, can enable around twice the density when compared against existing fiber cabling technologies, which grants them a very efficient solution for supporting different scenarios based on 5G network fronthaul. Moreover, the design of fiber ribbons allows them to be spliced by using simple splicing techniques while providing much higher density. Ribbon fibers solutions, initially widely used in data centers for short distance connections, is now considered here as a viable and elegant solution also for 5G network fronthauls. Indeed, ribbon fibers can support spatial channel diversity and potentially achieve further system capacity enhancement when combined together with advanced modulation formats [3] and dynamical resources allocation techniques [4].

5G mobile communication technologies [5], [6], along with hybrid solutions based on optical fiber links [7], [8], have become a prospective candidate to support the vast volume of data traffic generated by today's society. One of the biggest challenges recently faced by telecom providers is to meet demanding requirements of data traffic capacity in ultra-dense urban areas like metropolitan areas and hot-spot areas such as football stadiums with thousands of users highly concentrated in a small geographical region, where the footprint is critical and new network architectures should be considered. Accordingly, the cloud (also called centralized) radio access network (C-RAN) fronthaul architecture [9]-[11] can potentially overcome the capacity and coverage drawbacks as well as latency constraints of today's limited technologies, and consequently reduce the footprint. This new concept of fronthaul architecture, C-RAN fronthaul, provides several benefits not only in terms of technical specifications like capacity and network coverage, but also by increasing the network flexibility and wisely controlling operational costs. In

C-RAN fronthaul deployments, the (remote) radio heads (RHs) are connected to centralized baseband units (BBUs) using analog or digital radio-over-fiber (RoF) techniques and protocols [12]. This network section, from the BBUs until the remote RHs, is called fronthaul.

Moreover, 5G C-RAN infrastructure can support larger network capacity over smaller-cells such as densely deployed short-range base stations using millimeter wave (mmWave) frequencies [13]-[15]. MmWave frequencies with multiple bands within the frequency range of mmWave (30~300GHz) have been recently introduced as a potential technique for radio-based wireless connections to complement optical solutions. The vast amount of bandwidth available in the mmWave range is ideal to support higher data rates and large bandwidths, with mmWave-based wireless front- and backhauling interfaces delivering seamless connections. Moreover, beamforming can be implemented to mitigate high path losses in such a range of frequencies. Beamforming techniques can focus the transmission and reception of a signal energy into smaller regions of space, which brings improvements in throughput and energy efficiency. Thus, the mmWave spectrum-based techniques are part of 5G C-RAN fronthaul.

The 5G fronthaul infrastructure aims to support primarily a 1000 fold increase in current network capacity, user data rates 10 to 100 times higher than the current standards, and latency levels down to 1 ms; all under similar cost- and energy-expenses as provided by today's technologies. Therefore, in this paper we introduce and address the main features of the technologies responsible for the implementation of 5G C-RAN fronthaul networks that will most likely be responsible to support these performance requirements and eventually become part of the new 5G mobile standards. These technology enablers, can provide increased performance, better coverage, and a closer integration across multiple technologies, such as the following: ribbon fibers, wavelength-division multiplexing, C-RAN, radio-over-fiver, and millimeter wave. These technologies pave the way towards a truly efficient fronthaul infrastructure for 5G mobile communications with seamless connectivity for millions of devices and quality-of-service guarantees in terms of latency for the first time ever in communication history.

Furthermore, in this paper, we also address the ongoing

build up and development of the 5G Brainport testbed located in Eindhoven, mainly surrounding the TU/e campus, towards an open environment platform for validation and test of end-to-end emerging applications based on 5G systems. The Eindhoven 5G Brainport is a testbed platform that uses a unified open framework for seamless interoperability and orchestration of underlying hardware components to offering fast service creation and trial setups for validation of different use cases for vertical industries. We further introduce potential 5G-based use case scenarios to be exploited. We also address the main aspects of C-RAN fronthaul architectures and current challenging network scenarios, where service coverage can be considerably improved by means of 5G systems.

II. 5G BRANPORT TESTBED EXPERIMENTAL FACILITIES

The 5G Brainport testbed under ongoing development in Eindhoven provides a complete experimental platform for pilot tests and assessments of several distinct 5G use cases. The Eindhoven 5G Brainport testbed uses a unified open framework for seamless interoperability and orchestration of underlying hardware components so that fast service creation and trial setups can be offered for validation of core 5G key-performance indicators (KPIs) according to different use cases. In this way, the 5G Brainport offers an ultra-reliable low latency communications (URLLC) platform with a highly heterogeneous pool of resources to support different requirements, which enables the 5G KPIs targets over a versatile platform for an entire range of services. Figure 1 illustrates part of the Eindhoven 5G Brainport platform located in the TU/e campus. In addition, the Eindhoven 5G testbed operates over a metro-optical network and offers ultra-reliable connectivity for delay sensitive and bandwidth-hungry applications by merging real-time sensor data and offloaded tasks with big data analytics. The Eindhoven 5G Brainport platform allows validation and exploitation of several vertical use cases scenario such as agri-tech farming, and virtual reality as well as 360° video in a highly dynamic and integrated testbed.

Furthermore, the testbed platform includes an advanced channel sounder to allow radio and system performance evaluations in direct connection with channel characterization. The testbed supports both enhanced mobile broadband
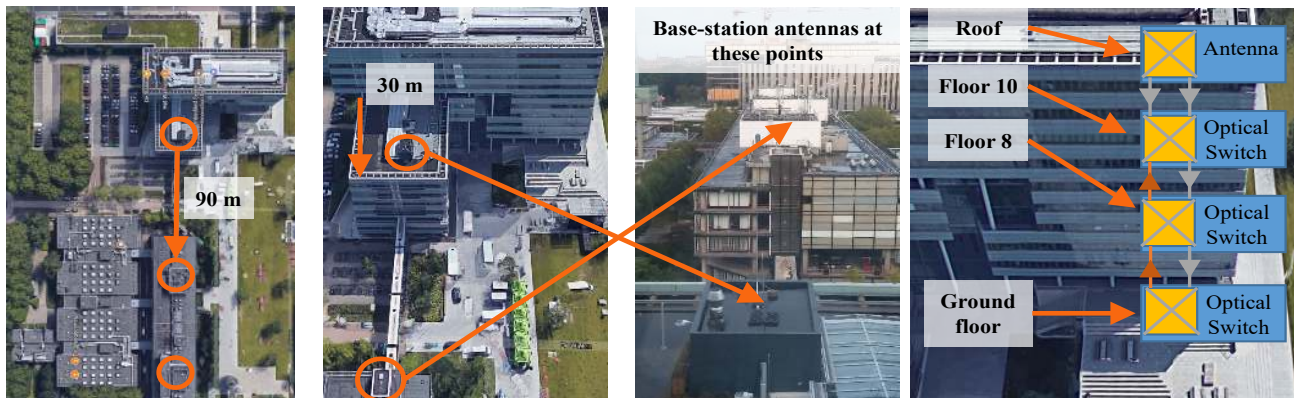

Fig. 1. Inter-building and intra-building communication in the TU Eindhoven campus as part of the 5G Brainport testbed platform.

(eMBB) and URLLC services through the combination of improved dynamicity of the optical and radio techniques and dynamic management of 5G applications. Besides that, the 5G platform testbed is further connected with the Dutch national and European networks, which allows not only functionality on its own, but also to be combined with a large scale test platform that ensures usability beyond the scope of current technology. The 5G platform uses a C-RAN-like structure as the new 5G fronthaul concept supporting both digital and analog radio-over-fiber deployment, mmWave signals, optical beamforming, massive MIMO, and SDN functionalities. In this fashion, the 5G Brainport platform paves the way beyond the boundaries of current technology by exploring optical infrastructure elements in a disaggregated multi-vendor environment.

Given the involvement in a number of 5G-PPP Phase 2 projects, the Eindhoven 5G Brainport experimental facilities will be used to initially carry out three vertical use cases: 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 improve the synchronization among drones. The use cases target the following 5G KPIs: ultra-low latency down to 1 ms with only 10 µs data plane jitter, 99.99 % reliability and availability, and mobile services with high mobility supporting speeds over 200 km/h.

New network architectures can be evaluated according to core functionalities so as to increase capacity and, the number of supported users, to support virtualization as well as flexible services, and software-defined networking capabilities. There is also an ongoing effort towards developing physical connections between intra- and inter-buildings as shown in Figures 1 and 2, connecting the local facilities and the new 5G infrastructure. Intrabuilding connections exist as part of the testing platform, with BBUs located on the 10th floor connected to the 8th floor using optical fiber. This can be useful for RoF transmissions using mmWave antennas with different wireless distances to enable upstream and downstream communication of a 5G system. Next, the radio

link of the RoF signal is located in the 6th floor terrace, and connected separately to another RoF link located in the 10th floor.

Distances over 90 meters for wireless transmissions can be achieved between 6th floor and the antenna placed on the rooftop of the building, see Figure 1. Another part of transmission segment is located in the Metaforum building at TU/e campus, connected also to the rooftop of a second building, using fibers according to specific requirements for both single and multi-wavelength transmissions, see Figure 2. Besides that, wireless transmissions can be achieved via the rooftop of the Metaforum building for distances over 75 m.

III. CLOUD-RAN FRONTHAUL

5G networks require a 1000-fold increase in capacity, which denotes increased backbone optical distribution network (ODN) requirements to support these data rates. Large number of antenna elements over small coverage cells e.g. femto-cells, to increase data rate per user will require large bandwidth availability in the fronthaul. Thus, future-proof solutions should expand the capacity limits while providing seamless integration among technologies for reducing the overall cost and energy consumption.

Energy consumption in cell sites is responsible for a large portion of the overall network cost and has become a key factor to be taken into consideration. The deployment of passive networks that bring optical fibers near or very close to the antenna premises, known as fiber-to-the-antenna (FTTA), can be part of the power consumption solution. FTTA is a term used to describe network architectures of high performance transmissions based on optical fiber technology, where fibers from the baseband unit (BBU) are connected all the way to antennas in the remote radio head (RRH). Moreover, this kind of solution allows RoF signals to be generated and transmitted through a fiber segment to reach an antenna placed in the RRH. This can be clearly understood via Figure 3, where a FTTA link rolling out from the CO to the RRH is illustrated. Notice that the BBU is located in the CO and not in a cell site cabinet near the RRH, hence several BBUs can be centralized in the CO location rendering a new mobile network paradigm, the so-called C-RAN fronthaul. In general, a C-RAN fronthaul architecture regards the relocation of BBUs from the RRH premises to the CO site creating a centralization of BBUs. Such a paradigm can grant the network several advantages like higher flexibility and manageability, space released in the RRH and reduced power consumption.

Figure 2. Fibers and antennas facilities for radio-over-fiber transmissions via the rooftop of the Metaforum building at TU/e.
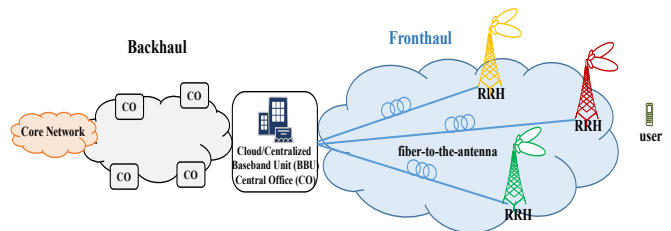

Figure 3. The 5G C-RAN fronthaul with cloud baseband units and fiber-to-the-antenna connections to the remote radio head.

Traditionally, RHs and BBUs were physically located at the same cell tower with a coaxial wire connection from the top of the tower (RHs) to the bottom of the tower (BBUs). Once this link was replaced by optical fiber, the BBUs sitting at each tower have been centralized at a distant location, and this new connection between the now remote RHs (RRHs) and stacked centralized BBUs (or more recently known also as single cloud-BBU) is referred to as fronthaul.

In addition, antennas can be placed in a longer distance from the CO, extending the reach since they are connected by fiber links as shown in Figure 3. Furthermore, the introduction of fiber ribbon in the C-RAN fronthaul can be seen as a novel approach towards the implementation of flexible, robust and high capacity networks. Indeed, the overall fronthaul infrastructure will call for an upgrade compatible with advanced radio transmission and space-division multiplexing (SDM) techniques. To decrease per fiber duct costs by placing as many fibers in a duct as possible, ribbon cables can nearly double the fiber density for a typical duct, enabling several fibers go to into spaces that were previously too small for such numbers. Accordingly, the lighter weight and smaller diameters of ribbon fibers can decrease installation costs and enable longer length reach to be used in C-RAN network fronthaul infrastructure. Figure 4 shows a possible solution based on ribbon fibers for 5G C-RAN fronthaul. Also illustrated the transverse view of a ribbon fiber in a loose tube.

Notable, ribbon cables can potentially provide several different fiber channels and consequently afford a huge amount of bandwidth transmissions and simultaneous connections. The ultra-compact ribbon fibers have great mechanical properties, are both easy to handle and compatible with legacy optical components and can be rolled out in a simple way to provide broadband services in the network areas illustrated here. In this way, different networking scenarios can be successfully satisfied, even scenarios that require a concentrated coverage like, for example, a musical concert or a popular sport event like a football match as exemplified in Figure 5a with thousands of users highly concentrated in a small geographical region. Hence, ribbon fiber-based schemes are suitable and feasible for deploying 5G C-RAN fronthauling to attend hot-spot scenarios coverage with several users and challenging technical environment conditions. The here so-called "B-Box" device is responsible for the communication and software-defined network programming.

Another interesting networking coverage scenario is illustrated in Figure 5b, where an ultra-dense area such as metropolitan areas with plenty of enterprise buildings and shopping malls with high density connections demand can be covered through ribbon fiber technology. Interestingly, only a single loose tube with rollable ribbon fibers is used as a solution for connecting fibers from the CO site to the antenna premises and delivering broadband communication. Denser fiber techniques such as the rollable ribbon fibers are perceived here as a potential alternative solution to deploying fronthaul infrastructure in a way that it can satisfy the stringent key performance indicators of 5G systems.

Furthermore, a rollable ribbon fiber cable is made of several monocoated optical fibers arranged linearly, which grants the optical fiber ribbon to be rolled up easily and accommodated very tightly [16]. Accordingly, this kind of fiber has a smaller diameter and weight and can provide a higher density as they are rollable into a smaller package than conventional flat ribbon fibers, with each of their individual fiber ease to be manipulated. This rollable ribbon, as also conventional optical fiber ribbons, is compatible with today's mass fusion splicers and multiple-fiber connectors [2]. Therefore, ribbon fibers are indeed an appealing alternative for 5G fronthaul networks, where several fibers can be used to connect and cover each small-cell antenna sites like lampposts via traditional ribbon, rollable ribbon, or loose-tube cables.

Although ribbon fibers are indeed a viable solution to C-RAN fronthauling, WDM technology can also be exploited in the fiber domain so as to enable a higher throughput while maintaining compatibility with legacy techniques as well as backhaul infrastructure [17]. Accordingly, several simultaneous channels at 10 Gb/s line rates or above can be supported via WDM technology, increasing even further the network capacity and still using passive techniques with unpowered devices to satisfy energy consumption requirements. Dense WDM technology can scale capacity for example up to 80 channels (wavelengths). This alternative solution for C-RAN fronthaul considerably reduces the installation and maintenance costs when compared to traditional mobile fronthauling based on several RRH installations and coaxial wire connections. Finally, WDM-

Figure 5. Example of 5G mobile networking coverage scenarios. a) A hotspot network scenario using ribbon fibers. b) An ultra-dense scenario under ribbon fiber solution.
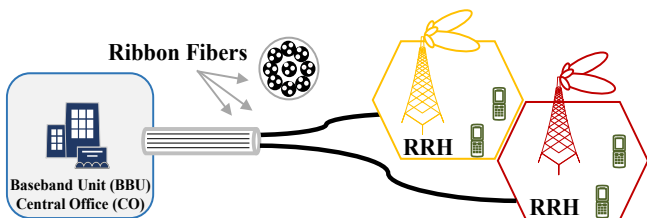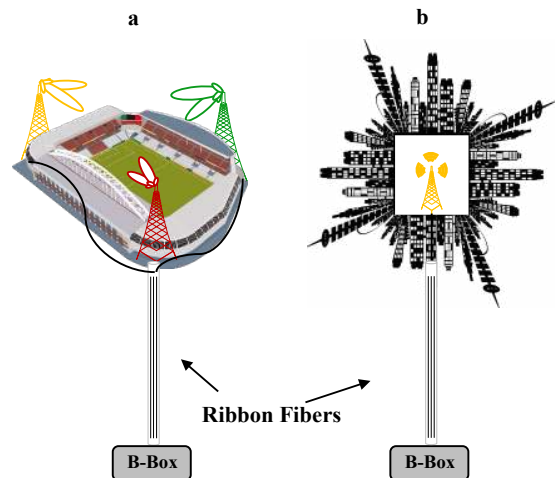

Figure 4. Proposed ribbon fiber solution with several fibers connected to a remote radio head. The inset shows the transverse view of a ribbon fiber.

based C-RAN fronthaul can make use of a single fiber to connect several RRHs to BBU sharing the same link via different available WDM channels. Nevertheless, ribbon fiber or WDM are not standalone solutions to provide coverage to hotspot or ultra-dense areas like the scenarios illustrated in Figure 5. As a matter of fact, mmWave technology also plays a fundamental role in the 5G fronthaul infrastructure to proportionate high data rate links to end-users. For example, a large number of RRH antennas can be placed surrounding a stadium premises or shopping malls so that the whole area can be covered with the help of mmWave technology.

Normally, a RoF network based on mmWave transmits a digital baseband signal through a fiber link, undergoes optical to electrical conversion (O/E), digital to analog conversion and upconversion to the radio frequency, and then is radiated and detected. Thereby, the O/E conversion represents the transition from the fiber link to a radio frequency signal at mmWave frequencies, which denotes the main step in bringing advantages to RoF-based networks.

The use of analog RoF with the radio frequency signal generated directly by the beating on a photodiode and thus no necessity for digital to analog conversion or RF upconversion, which allows the network to use larger modulation bandwidths readily available in the optical domain, and also enables the centralization of critical equipment such as network control, and radio frequency oscillators. Once at an intermediate frequency or baseband, the signal can be easily modulated onto an optical carrier for transmission through fiber. Hence, fiber optics, photonic up-conversion and wireless transmission combined together, can benefit from the advantages of both wireless and optical domains in a way that fiber optics bring the ability to easily bridge large distances and use very large modulation bandwidths, while wireless links allow for easy, fast and flexible deployment, and additional simplification of centralized networks [18], [19].

Generally, the detection and down-conversion of radio frequency signals play an important role in mmWave systems, with the recovery of the transported baseband signal being the direct complement to up-conversion and radiation of the radio frequency signal. Amongst several different methods to retrieve the transmitted data, such as direct remodulation, optical envelope detection, and optical down-conversion to an intermediate frequency or directly to baseband [20], the electrical down-conversion method stands out due to its simplicity and cost-effectiveness. The emergence of mmWave techniques and the transition from the overcrowded conventional wireless bands below 6 GHz towards mmWave radio frequency ranges are seen as a fundamental step to enabling large data rate transmission capabilities and large coverage in 5G fronthaul networks.

Millimeter wave spectrum is the band of spectrum between 30 GHz and 300 GHz, and receives this name due to the short wavelengths of waves that can be measured in millimeters at these frequencies. Although the mmWave bands extend all the way up 300 GHz, it is the bands from 24 GHz up to 100 GHz that are expected to be used for 5G mobile systems [21]. They can be used for high-speed wireless communications, with the early interest being in the bands just below 30 GHz and the

best candidate frequencies for use around 60 GHz (V-band) due to its large available spectrum and unlicensed bands, and hence higher capacity and larger number of users accommodated. The short wavelength of mmWave carriers renders it possibilities to fit a large number of antenna elements within the same or even a smaller footprint as current sub-6 GHz antennas. This allows the deployment of several antenna arrays with thousands of antenna elements, which was impractical in previous generations of mobile systems due to form factor and size restrictions of such elements.

Initially, the use of high frequency bands was considered unsuitable for mobile communications due to the high propagation losses and the ease with which signals are blocked by building materials and foliage. Although these challenges might place limitations on mmWave deployments, new antenna technologies together with a better understanding of channel characteristics enable several network scenarios to be considered. In addition, the mmWave cell sizes will be smaller and higher in density, which provides high throughput and efficient use of spectrum as frequencies can be reused over relatively small distances. It is expected that outdoor cell sizes will be typically 50 m to 100 m and indoor high-density deployments might be as small as 10 m. However, an important part of 5G mmWave performance is dependent on line-of-sight signal propagation and antenna design.

As a conclusion, the implementation of new 5G mobile standards and the use of mmWave spectrum is expected to be revolutionary. The mmWave bands being made available for mobile networks will provide increased performance, better coverage, and a closer integration across multiple wireless technologies.

IV. CONCLUSIONS

In this paper, we have addressed and reported the principal technologies part of the next generation mobile fronthauling networks, namely 5G fronthaul. We also described the main features of these technologies and illustrated their benefit via current and challenging bottleneck network conditions by involving real world scenarios with high demand for innovative solutions. These technologies, ribbon optical fibers, RoF, passive WDM, mmWaves, will be most likely implemented in the 5G fronthaul infrastructure. Among these technologies, the main technical challenges remains to to be addressed: cost efficient hardware solutions for RoF transceivers and simple adaptation of RoF techniques over ribbon fibers, optical beamforming in integrated photonics, seamless interfaces between the ribbon fiber media and the radiating elements in the RU sites, and remote power distribution to RUs from CO premises.

We have further introduced the 5G testbed platform under development at TU/e Eindhoven, the Eindhoven 5G Brainport. The 5G Brainport testbed is perceived as a complete validation and evaluation platform for a large range of emerging applications based on 5G KPIs. By its turn, we also addressed the principal 5G KPIs considered essential for reliable operation of 5G mobile systems and we have described different use cases that rely and implement them. The discussed technologies are regarded as potential candidates to

deploy next 5G fronthaul infrastructure, where higher bandwidth transmissions, seamless connections, vast number of users, and guaranteed ultra-low latency services, are major network requirements of a fully integrated and successful C-RAN fronthaul concept providing scalability, manageability, and flexibility.

ACKNOWLEDGMENT

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