Testing Facilities for End-to-End Test of Vertical Applications Enabled by 5G Networks: Eindhoven 5G Brainport Testbed

Idelfonso Tafur Monroy[1,*], Thiago R. Raddo[1], Simon Rommel[1], Chigo Okonkwo[1], Nicola Calabretta[1], Ulf Johannsen[2], Gijs Dubbelman[2], Jesse Scholtes[2], and Ben Rutten[2]

[1]Institute for Photonic Integration, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands
*[2]Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands, *e-mail: i.tafur.monroy@tue.nl*

ABSTRACT
The key-performance indicators (KPIs) that will be delivered by 5G networks such as extremely low-latency, high capacity, robustness and highly flexible network are key enablers for applications such as autonomous driving, cooperative robotics, transport and processing of large volumes of video and images, to name but a few. This paper presents the ongoing build up and deployment of the Eindhoven based 5G-Brainport testbed towards an open environment for validation and test of end-to-end applications benefitting from the 5G KPIs.
Keywords: 5G, RoF, mmWave, massive MIMO, KPI, C-RAN.

1. INTRODUCTION

The next wave of innovation in 5th generation (5G) mobile networks will certainly generate numerous business opportunities and large impact on the global economy, mainly driven by novel low latency applications, high bandwidth broadband services, and robust wireless connectivity for robotics [1]. New business models of services will increase the popularity of these applications even further and make them part of everyday life, where people will have convenient access to such applications on a regular basis. With that in mind, vertical industries will not be able to rely on the existing mobile network infrastructure to support strict 5G key performance indicators (KPIs) and the exponential increase of mobile data traffic loads. Technology development is facing a race against time, not only for satisfying the requirements of 5G KPIs, but also for meeting new business concepts. To this aim, diverse technologies such as millimeter-wave (mmWave) [2], fiber-wireless (FiWi), cloud radio access network (C-RAN) [3]-[5], massive multiple-input multiple-output (MIMO) [6], beamforming, and software-defined networking (SDN), among several aspects [7], are being put together to meet the specific KPIs and to adapt on-the-fly to the ever-increasing traffic demands of today's society.

In this context, the Eindhoven 5G Brainport testbed complex offers an attractive open environment for pilot tests as well as evaluations for applications and scenarios that require the new stringent 5G KPIs to be met, like, e.g., robot-to-robot communication, FiWi fronthaul to robot, robot-to-drone, 5G mobile-operated autonomous vehicles, to name but a few. To do so, the Eindhoven 5G Brainport testbed complex will deploy a unified open framework for seamless interoperability and orchestration of underlying hardware components, which can offer fast service creation and trial setups by vertical industries for the validation of core 5G KPIs according to different use cases. Indicatively, broadband access in 5G KPIs is expected to reach 1000x the capacity of current 4G long-term evolution technology and an ultra-low latency down to 1 ms, while maintaining low-cost and power consumption. Hence, an ultra-reliable low latency communications (URLLC) platform with a highly heterogeneous pool of resources that can support different requirements has been developed and has its main features presented in this paper, enabling the evaluation of 5G communication targets over a versatile use case platform over the entire range of URLLC services.

Furthermore, the Eindhoven 5G Brainport testbed, under development in the TU/e campus, operates over a metro-optical network with edge computing capabilities and offers ultra-reliable connectivity for delay sensitive and possibly bandwidth-hungry applications by merging real-time sensor data and offloaded tasks with big data analytics. It exploits a unique synergy of optical and wireless technologies employing advanced optical space-division multiplexing (SDM) technologies via multi-core optical fiber links and optical beamforming to enable flexible network architectures with advanced functionality, especially focusing on automotive and robot use cases. Accordingly, robotic use-case validation trials requiring increased capacity and low latency to control and coordinate robotic processes can become a reality, as do automotive scenarios, where cars require a fast and ultra-reliable connection to deliver information regarding their environment, location and road safety. The Eindhoven 5G Brainport platform allows validation and exploitation of these scenarios in a highly dynamic and integrated testbed. Figure 1 shows part of the Eindhoven 5G Brainport platform located in the TU/e campus.

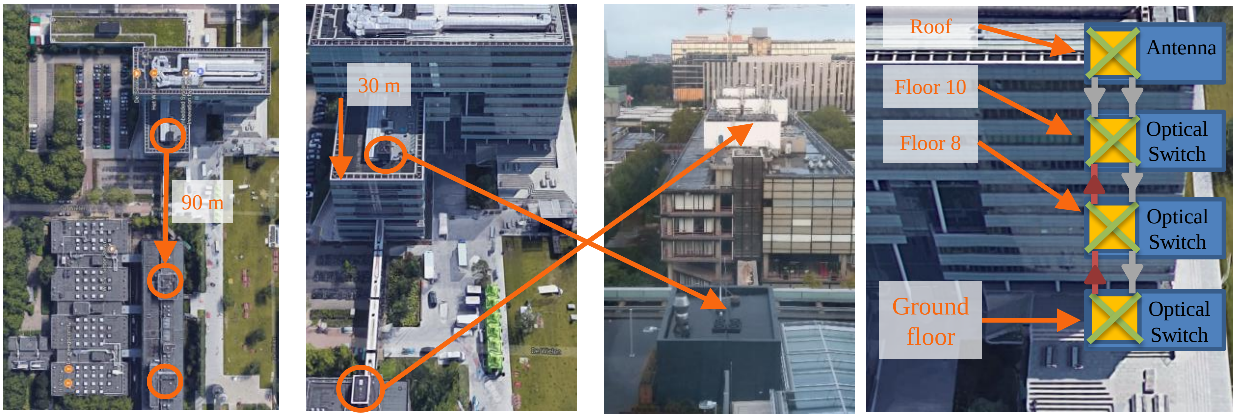

Figure 1. Inter-building and intra-building communication in the TU/e campus, part of the 5G Brainport testbed.

The 5G Brainport platform is based on the C-RAN concept [5] that accounts for the fronthaul segment [8] between the central office (CO) and remote unit (RU) with radio interfaces to the end user equipment. The testbed platform is built on fiber optics, supporting both digital and analog radio-over-fiber fronthaul [9], [10], and focusses on low latency, high data rate applications requiring mmWave signals [11]. To achieve the data-rate goals, 5G networks will employ novel massive MIMO systems and eventually use more bandwidth at the mmWave frequencies. This innovative deployment demands on large-scale array antenna systems with hundreds of active antenna elements operating fully coherently. The use of a large number of antenna elements helps to focus the transmission and reception of signal energy into ever-smaller regions of space, which, brings improvements in throughput and energy efficiency. The development of integrated silicon-based antennas for future 5G base stations are is one of the goals of the European project known as SILIKA [12] with ongoing research under the 5G platform.

Figure 2 illustrates part of the concept currently under development in the 5G Brainport testbed platform. It is worth mentioning that with the use of optical space division multiplexing and multi-core fibers, 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 RU architecture while maintaining advanced RF beam shaping and steering capabilities. By its turn, the radio interface, which combines millimeter 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.

The testbed platform includes an advanced channel sounder to allow radio and system performance evaluation in direct connection with channel characterization. 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 with the Dutch national and European 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 (ROADM, flexible transponders and transceivers etc) in a disaggregated multi-vendor environment. These solutions require low-cost optical switching technologies and high capacity, as well as highly programmable flexible transponders.

Given the involvement in a number of leading 5G-PPP Phase 2 projects, the Eindhoven 5G Brainport experimental platform facilities will be used to initially carry out three verticals 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 TUe'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. The three use cases are presented in the next subsections in details. The 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.

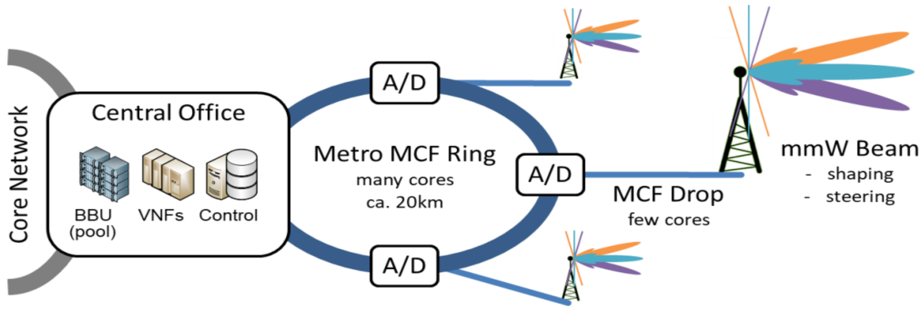

Figure 2. The Eindhoven 5G testbed based on mmWave and optical space division multiplexing technologies in support of 5GPPP project blueSPACE.

2.1 Automotive Vehicle to Everything (V2X) Service Use Case Scenario

This use-case addresses the development of innovative mechanisms and techniques for automotive communication applications. Nowadays, most of the cars manufactured in the premium segment have a range of embedded connectivity solutions to enable in-vehicle communication and connectivity to the surrounding infrastructure. In addition, vehicles are being improved to exchange information with other vehicles (V2V) to avoid collisions and with the road-side infrastructure (V2I) for traffic signal timing and priority. In addition, vehicles are being rolled out with vehicle to internet services (V2N) for real-time traffic routing or management services. Vehicle to pedestrian (V2P) information exchange also enables safety alerts to and from pedestrians and cyclists. Many vehicles being developed already incorporate a limited form of 5G capable-technology to support reduced latency, increased reliability and high throughput vehicle to everything (V2X) messaging in a highly dense connectivity environment. Figure 3 shows the highly challenging connectivity demands for future vehicles, including bandwidth and latency. Briefly, the initial flow begins with the processing of information from sensors mounted on the vehicle and helping the vehicle to perceive its surrounding in such a way that an additional wireless communication sensor can help the vehicle to connect with other vehicles and with the local infrastructure to assist autonomous driving. Then, algorithms decide how the car can proceed in a route for example via a path planning algorithm. Finally, with a combined picture of the vehicle surroundings and route, the vehicle control algorithms take action and determine how much the car should accelerate or brake and steer in order to safely and accurately follow the determined path.

Three discrete trials can be considered: a) automated overtake procedures, where the semiautonomous or fully-autonomous procedure must be activated upon detecting a slow moving vehicle, requesting updated information on the condition of the roads (traffic, accidents and/or infrastructure) and obtaining information from the cars around the vehicle, b) collaborative collision avoidance, where advanced driver assistance offers radar-based sensor feedback to the driver without knowledge of what new obstacles beyond what forward and rear sensors may provide. 5G enables a new feature of providing information from infrastructure, other vehicles and from the overall network management platform of what collisions are occurring and to take evasive action. First, by collaboratively coordinating the routes of all vehicles, the trajectories of all vehicles/road users are managed to avoid collision. This requires regular transmission of cooperative awareness messages that have higher priority if the client vehicle is in danger of collision or has collided, so that vehicles in the vicinity of the client vehicle become aware. The latency aspect of this use case is particularly critical. Finally, c) vehicle platooning is considered as a use-case, where, in case of convoy management requirements, the involved vehicles plan a path for efficient vehicle traffic flow using the monitoring of data from installed sensors on the vehicles and along the road side infrastructure units to gather information on the environment from neighboring vehicles and coordinate their movement as a platoon.

2.2 Cooperative Autonomous Soccer Robots

This use-case exploits the low-latency and high throughput capabilities of 5G for cloud controlled multi-robot collaboration in highly dynamic environments. TU/e is 3 times world champion and 10 time finalist of RoboCup, where the long time goal is to win against the human world champion team by 2050. Each robot member of the team is equipped with a set of sensors (RGBD, IMU, odometry, 360° omni vision) and associated processing units used for the constantly updated representation of the actual robot world. The sensor data is abstracted down to the location of the robot itself the soccer pitch, its team members, opponents and the football. As the game is highly dynamic, with speeds up to 5 m/s, accurate and low latency position information is function critical. Thus, each team member robot constantly exchanges abstracted world model information used to minimize the error in its own environmental perception.

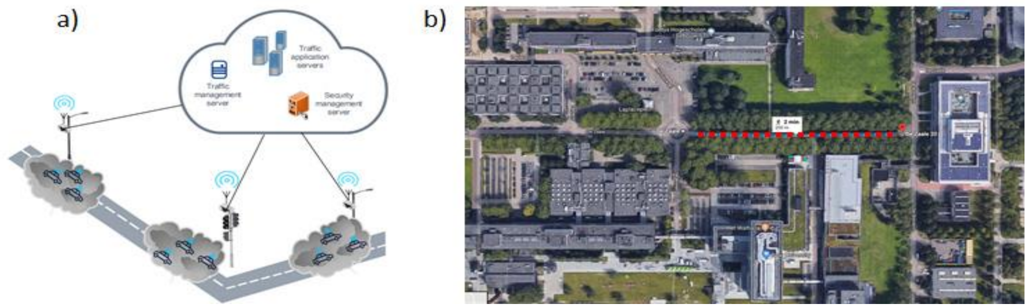

Figure 3. a) Interaction of vehicles to infrastructure road side units (RSUs) and application servers at the edge; b) the location of the vehicle to everything (V2X) experimental facility in the TU/e campus.

On the top of that, each robot makes and exchanges predictions of potential future world states that are used to determine the tactics and game mode of the team (attack, defense, strategy and team roles). Current wireless communication solutions (Wi-Fi at 2.4 GHz or 5 GHz) limit the total exchange rate for a team to 2.5 Mb/s. Higher rates result in increased package losses, latency and jitter effects due to limited area traffic capacity. This heavily limits the teams' collaboration capabilities. 5G communication technology enables the use of central, cloud based world models that combine the information of raw sensor data with big data resources and computation capacity to execute complex and coordination intensive tasks. As such, 5G technology will allow for offloading the raw sensor data into a cloud-based centralized world model to better coordinate the robots movements in a game of soccer.

2.3 Cooperative Autonomous Drones

This use-case concerns the possibility of cloud-based real time control of cooperative autonomous drones and robots over 5G and is schematically illustrated in Fig. 4. High-bandwidth rates allow for robots to share information in a runtime fashion, which is similar to how humans share their knowledge over the Internet. This allows robots to communicate their knowledge to other robots instantaneously, which enables efficient storage and redistribution of learned concepts and task information on a global level. Once this knowledge can be made available in unified storage locations, the idea of centralized learning and planning is realized; one central system that receives robot knowledge on a global level, stores learned concepts, and controls thousands of robots in a ubiquitous and highly optimized manner. In this fashion, the heavy computations required for the processing of data and machine learning of task fulfilment strategies can be run centralized, rendering robots to only require small hardware control modules and lightweight client interfaces.

By its turn, a drone manages its own sensor information (IMU, on-board cameras, LIDAR) for stabilization and motion planning, where synchronization among different drones is achieved via a central unit to which drones send a small amount of data via XBee or Wi-Fi, and receive simple correction commands to ensure movement and light

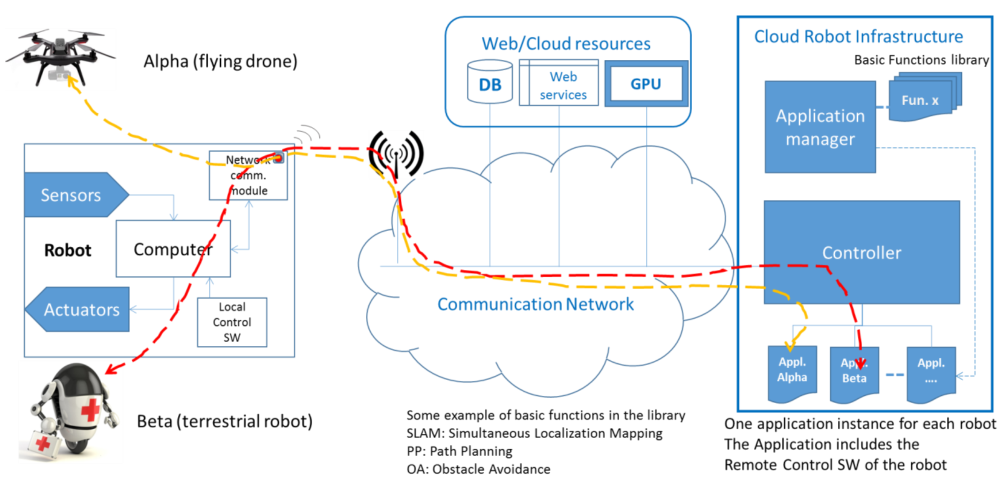

Figure 4. A simple scheme for the proposed centralized system for 5G-based cooperative autonomous drones and robots. DB: data base; GPU: graphics processing unit [13].

synchronization. An important bottleneck is the poor reliability of Wi-Fi and the limited data rates achieved with XBee, constraining the amount of coordination data and imposing hard constraints on the achievable coordinated maneuvers. However, the use of 5G systems will eventually allow several improvements and deliver the necessary KPIs, truly enabling such an application. In fact, the extremely high reliability, the low latency and jitter, opens the possibility to off-load the motion planning tasks to the cloud which can then be directly coordinated by a central unit; the high 5G throughput will allow to send high-rate sensory data including on-board camera data, and to receive non-trivial coordination and control commands at high rate. For concreteness, this use case employs a small number of drones (<10) working as a proof of concept of cloud control over 5G. Nonetheless, it is worth mentioning that the 5G based approach is scalable from a resource perspective, to a larger number of drones with only very limited computational abilities, contrarily to state-of-the art approaches where each drone requires a costly processor.

3. CONCLUSIONS

In this paper, we have briefly introduced and described the concept behind the Eindhoven 5G Brainport testbed and its main technologies and use cases. In addition, we introduced the 5G KPIs that have become crucial requirements for reliable operation of 5G communication networks and described the three different use cases that are being developed. Hence, we perceive the Eindhoven based 5G-Brainport testbed as a complete validation, evaluation and test platform for a large range of applications based on 5G systems.

ACKNOWLEDGEMENTS

This work is supported by the H2020 5GPPP Phase II projects 5G-PHOS (grant agreement No. 761989), blueSPACE (grant agreement No. 762055) and Metro-Haul (grant agreement No. 761727). The SILIKA project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 721732.

REFERENCES

[1] G. Brown, “Exploring 5G new radio: use cases, capabilities & timeline,” *Qualcomm White Paper*, 2016.

[2] M. Xiao, S. Mumtaz, Y. Huang, L. Dai, Y. Li, M. Matthaiou, G. K.Karagiannidis, E. Bjornson, K. Yang, C.-L. I, and A. Ghosh, “Millimeter wave communications for future mobile networks,” *IEEE J. Sel. Areas Commun.*, vol. 35, no. 9, pp. 1909-1935, 2017.

[3] I. A. Alimi, A. L. Teixeira, and P. P. Monteiro, “Toward an efficient C-RAN optical fronthaul for the future networks: a tutorial on technologies requirements challenges and solutions,” *IEEE Commun. Surveys Tuts.*, vol. 20, no. 1, pp. 708-769, 2018.

[4] F. Mukhlif, K. A. Bin Noordin, A. M. Mansoor, and Z. M. Kasirun, “Green transmission for C-RAN based on SWIPT in 5G: a review,” Wireless Networks, 2018.

[5] A. Checko, H. L. Christiansen, Y. Yan, L. Scolari, G. Kardaras, M. S. Berger, and L. Dittmann. “Cloud RAN for mobile networks - a technology overview,” *Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 405-426, 2015.

[6] M. Feng, S. Mao, and T. Jiang, “Joint frame design resource allocation and user association for massive MIMO heterogeneous networks with wireless backhaul,” *IEEE Trans. Wireless Commun.*, vol. 17, no. 6, pp. 1937-1950, 2018.

[7] F. Boccardi, R. Heath, A. Lozano, T. Marzetta, and P. Popovski. “Five disruptive technology directions for 5G,” *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 74-80, 2014.

[8] T. Pfeiffer, “Next generation mobile fronthaul and midhaul architectures”, J. Opt. Commun. Netw., vol. 7, no. 11, pp. B38-B45, 2015.

[9] J. J. Vegas Olmos and I. Tafur Monroy. “Reconfigurable radio-over-fiber networks,” *J. Opt. Commun. Netw.*, vol. 7, no. 11, pp. B23-B28, 2015.

[10] S. Rommel, S. Rodriguez, L. Chorchos, E. P. Grakhova, A. K. Sultanov, J. P. Turkiewicz, J. J. Vegas Olmos, and I. Tafur Monroy, “Outdoor W-band hybrid photonic wireless link based on an optical SFP+ module,” *IEEE Photonics Technology Letters*, no. 28, vol. 21, pp. 2303-2306, 2016.

[11] R. Puerta, S. Rommel, J. J. Vegas Olmos, and I. Tafur Monroy, “Optically generated single side-band radio-over-fiber transmission of 60 Gbit/s over 50 m at W-Band,” in *Optical Fiber Communication Cof.*, 2017.

[12] A. B. Smolders et al., "building 5G millimetre-wave wireless infrastructure: wide-scan focal plane arrays with broadband optical beamforming," IEEE Antennas and Propagation Magazine, submitted, 2018.

[13] 5G-PPP automotive working group, “A study on 5G V2X deployment,” *Online White Paper*, https://5g-ppp.eu/wp-content/uploads/2018/02/5G-PPP-Automotive-WG-White-Paper_Feb.2018.pdf