EXPLOR – A Novel Holistic Numerical Platform for Converged Optical-Wireless B5G Networks

Abstract—5th Generation (5G) communication systems are expected to undergo significant advances, with optical-wireless technologies being at the forefront of system design addressing key requirements targeting high performance, versatility and cost-effectiveness. The EU-funded EXPLOR project aims to develop a comprehensive modular platform with experimentally validated state-of-the-art component and system-level numerical models, as well as cognitive and adaptive features. It is a collaborative industry-academic driven project committed to creating a scientifically and socio-economically relevant outcome, enabling further innovation beyond 5G networks. The software will include libraries with novel use cases and scenarios targeting next-generation converged optical-wireless networks, and enable the deep academic and techno-economic considerations of relevant features such as high-end mm-wave frequency, adaptive and virtualized optical front-haul, femto-cell based communications, network cognition and dynamic cloud radio access network (C-RAN) environment functionalities. EXPLOR will provide a holistic insight into the field that will act as a tool for promoting and demonstrating future innovation in the field.

Keywords—Beyond 5G Networks, Optical Fronthaul Virtualization, Femto-cell Design, Cell Densification, Network Centralization, Cloud-RAN, Passive Optical Networks

I. INTRODUCTION

The astounding growth rate of subscriber count and service versatility demands have driven mobile access standardization towards considerable strides since the 3G era, where mobile system platform has been re-engineered from network-centric to increasingly content-centric communications systems, positioning the end user as both consumer and producer of content [1, 2]. Such context and flow-driven heterogeneous operation of future networks is likely to envisage on-demand virtualized small-cells incorporating terabit connectivity and a dynamic cloud radio access network (C-RAN) environment for controlled centralization [3]. Even though today’s small-cell technology has already demonstrated Gigabit wireless transmission, current engineering paradigms based on exploiting multiple antenna technology and small-cell densification provide bounded improvement margin due to limited spectral availability. Hence, the necessity to migrate to higher frequencies in order to harness new spectral opportunities is widely accepted, with standardization bodies already placing significant focus on mm-wave frequencies beyond 40 GHz and service operators becoming highly involved in the evaluation of mm-wave technology best suited for mobile applications [1, 2, 4, 5]. However, high frequency operation leads to further cell size reduction (i.e. ‘femto’-cell technology) and centralized coexistence with first round deployment of 5G small- and legacy macro-cells – a scenario which promotes high loss and exceptional bandwidth demand threatening to offset its potential cost-effectiveness. Network centralisation efforts thus
increasingly turn to broadband fibre optic deployment, where a virtualized optical network sublayer may thrive in addressing the mentioned issues if efficiently streamlined over an effective and holistic, network-wide resource management via C-RAN orchestration [6], [7].

EXPLOR project is an initiative pursuing enabling technologies within the scenario of fiber-optic deployment foreseen as an “added-on” C-RAN feature highly compatible with femto-cell operation demands. It will target novel flexible multi-tech optical fronthaul (OFH) and RAN architectures with enhanced spectral, energy and area efficiency at lower cost per transferred bit, supporting legacy coexistence and high adaptability to novel services/devices (e.g. smart city and Internet of Things). EXPLOR platform will address the demand for novel link-level channel models and methodologies targeting the design and optimization of network performance, complexity and resource management in highly convergent, heterogeneous scenarios – resulting in a holistic training, engineering and research tool.

This paper is structured as follows. Section II outlines the project vision, while details surrounding the project’s main objectives and validation methodologies are provided in Sections III and IV, respectively.

II. EXPLOR VISION

![Fig. 1. EXPLOR project scenario. CO: Central Office; BBU: Baseband Unit; MUX: Multiplexing; FSD: Functional Split Design; RN: Remote Node; ONU: Optical Network Unit; RRH: Remote Radio Head.]

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Paired with the multiple-antenna technology, small-cells have the potential to significantly improve spectral efficiency, along with the line of sight probability contributing to reduced path loss [8]. In the first round of 5G deployment, small-cells are presently deployed in the sub-6 GHz band integrated with multiple antenna technology, where cell densification has already lead to significant improvements in spectral and area efficiency. However, it is still anticipated to fall short of the 20 Gb/s data rate stipulated by the IMT 2020 and beyond program [9]. In essence, transmission bandwidth still constitutes a dominant bottleneck as the wireless spectral availability in the microwave region grows scarce. Full alignment with standardization targets has firmly pointed the research community towards the millimetre wave region of vast unlicensed spectral opportunity for subsequent 5G roll-outs [1], [5]. Towards higher spectral availability and cell capacity bordering on terabit connectivity, the cell size ought to be driven further down to what we refer to as the femto-cell technology.

On the other hand, cell densification also delivers complex multi-tier interference scenarios and increased traffic fluctuation. As such, network centralization based on C-RAN paradigm is introduced to tackle traffic fluctuations selectively as per-access point, via intelligent and ubiquitous resource management and coordinated scheduling. Compared to distributed architectures, centralized approach brings strong potential for improved spectral and energy efficiency, and lower capital/operational expenditures (CAPEX/OPEX). Centralization, however, comes at cost of stringent latency requirements and high fronthaul (FH) transmission bandwidth penalties [11]. Hybrid architectures based on OFH are the right fit towards meeting those bandwidth demands.

Optical access has rapidly evolved past already widely deployed Gigabit technologies. Beyond improved bandwidth, spectral efficiency, application versatility, and cost-effectiveness of 100G-Passive Optical Network (PON), market dictates deploying next generation (NG) PON as part of a convergence solution [12], [13]. It still, however, faces the challenges of native spectral availability, and cost ramifications of the aforementioned bandwidth demanding RAN centralization [14], [15]. For instance, a typical LTE system adopting 2 antennas per cell requires roughly 20Gb/s of CPRI line rate - a significant penalty compared to the instantaneous signal bandwidth. Such high bandwidth penalties may considerably restrict highly attractive NG concepts like massive MIMO, and offset the expected cost benefits of C-RAN through prohibitively high OFH CAPEX/OPEX. Cost effective, virtualized and configurable OFH architecture is thus of high importance. Moreover, as diversity of broadband services grows, so does the necessity to address the network scalability beyond typical peak-provisioning approach. While a flexible OFH may assist cost effective on-demand resource management in a highly heterogeneous network scenario [10], optimized C-RAN functional split design may bring additional levels of system flexibility towards dynamic balancing of service requirements with system constraints [11].

EXPLOR network vision assumes integrated networking ecosystem, with legacy and emerging systems contributing in providing the best possible, context-driven network operation. As shown in Fig.1, the above discussed paradigms all provide the impetus for novel end-to-end architectures and enabling protocols, supporting heterogeneous environment by utilizing the available networking resources flexibly, adaptively and on demand. By adopting these enabling paradigms, EXPLOR aligns with 5G roadmap towards market relevant research and innovation beyond 5G networks. EXPLOR platform will enable innovation in both optical and wireless domains towards flexible, multi-tech architectures supporting coexistence, enhanced aggregate capacity and spectral/energy efficiency at reduced cost.

EXPLOR project will exploit the technical expertise of both the academic and industrial partners to enable relevant technology advances, effectively bring those advances close to the market, fulfill relevant and applicable inter-sectoral knowledge transfer - and foster lasting collaborations that大纲 the project lifetime. EXPLOR platform thus hinges on inter-sectoral collaboration, equipment and software sharing.
and pronounced training and knowledge transfer between the multidisciplinary academic and industrial partners.

III. OBJECTIVES

EXPLOR will follow the above outlined roadmap towards market relevant research and develop a holistic, integrated and flexible networking software. This will assure the upmost relevance of the platform as the training, engineering and research tool. As depicted in Fig. 2, EXPLOR project objectives are organized in four main categories of numerical development: virtual resource management; OFH architecture; femto-cell design and deployment; and machine learning aided cognition and optimization.

EXPLOR will focus on enabling holistic consideration of C-RAN orchestration that includes optical-wireless virtualization interface. This will enable the design of novel dynamic functional split (DFS) frameworks [20], [21], towards dynamically adjusting the protocol function allocation between cloud based virtual network functions and RRU according to adopted reference scenario and infrastructure constrains. Namely, we will pursue development of tools to enable optimization of latency, power consumption and capacity constraints in the OFH and RAN, over a well-coordinated allocation of tasks to various optical and RF network components. Special focus will be placed on enabling full-duplex OFH orchestration while considering both availability and performance of candidate CO transmitter architectures. We anticipate that such approach of holistic network resource management has a high potential to offer improved support to 5G networks and their future evolution, while remaining cost-effective for 4G, despite vastly different requirements for bandwidth, latency and topology. Moreover, as beamforming becomes more challenging at mm-wave frequencies, so does the intelligent scheduling across a large number of RRRs, due to additional levels of control required: in addition to power, the direction on both the BS and user end (UE) sides needs to be coordinated. As scheduling is one of the most challenging tasks in enhanced node BS (eNB) logic, enabling its successful scaling in a cost- and energy-efficient manner is of high relevance.

B. Introduction of Complex Femto-Cell Deployment Scenarios

Enabling innovation in beyond 5G network scenarios necessitates the consideration of coexistence of devices in complex, non-planar urban environments. However, typical stochastic geometry models treat all transceivers as 2D plane based, where tiers of base stations are mostly modelled as independent, homogeneous point processes. EXPLOR will address their extension to urban areas by introducing simulation modules accounting for non-homogeneous distribution of users and infrastructure, with the main focus on high end mm-wave frequencies. In turn, our focus on high end mm-wave operation further implies the challenge of mobility in the scenario of large beam steering gains required to overcome high propagation losses [22]. EXPLOR will thus also include modules that emulate user mobility in femto-cell deployment capable of quantifying the mobile network performance and providing a valid basis for the design of novel algorithms and protocols in beyond 5G scenarios. Newly developed models will be validated using system level simulators, considering both reference- and most realistic beyond 5G-scenarios.

The main focus of EXPLOR is in providing beyond state of the art accuracy versus tractability trade-off for such complex deployment scenarios and dynamically optimizing said trade-off for minimized computational latency [23]-[25]. Namely, towards a holistic network consideration, the platform will include models considering various levels of inter-node spatial correlation, where the choice of intensity functions will be optimized for scenario-specific accuracy and tractability trade-offs governed by the optical link performance at required mm-wave frequency. To assure optimal modelling choice for each scenario, the integration of femto-cell deployment toolset into the EXPLOR platform will be aided by machine learning procedures. EXPLOR will thus enable the design of efficient association rules, rate adaptation, beam steering strategies and handover policies, as well as the assessment of femto-cell design and deployment.

![Fig. 2. EXPLOR platform functional blocks. SDT: Software Defined Transceiver; ODN: Optical Distribution Network; SLS: System Level Simulator.](Image)
requirements while fundamentally considering the functional split and OFH designs.

C. Full-Duplex Optical Fronthaul Virtualization

In the adopted context- and flow-driven heterogeneous scenario based on virtual femto-cells, set-up on demand for terabit connectivity and orchestrated over a C-RAN environment for full functional split optimization [1], [3], [20], [21], highly virtualized optical network sublayer is required for holistic resource management [26]. The field of optical virtualization still faces key challenges targeting cost, complexity, scalability and fiber-wireless integration, particularly on optical hardware virtualization level [27], [28]. Bandwidth variable software defined (SD) transceiver concept is an attractive virtualization vehicle [28], [29], particularly when paired with virtualized subcarrier/modulator pooling concept towards addressing the lack of aggregation support critical for efficient infrastructure sharing [27], [30]. However, the interoperability of this approach with C-RAN and femtocell technology is yet to be fully investigated. Namely, the potential of adaptive pooling approach in the context of high capacity, long distance and high frequency mm-Wave transmission, supporting dynamic optical resource orchestration and functional split, is challenging [4], [27], [31].

EXPLOR will pursue transmission architectures and use-cases with potential to drive the overall network costs down by means of: i) optimizing the cost/complexity requirement for the electro-optic components comprising the central station; and ii) increasing the efficiency of dynamically centralized, fully coordinated and virtualized optical/wireless resource management. Following that approach, the platform will enable the investigation of relevant SD transmission designs and trade-offs, with the particular focus on developing the optical transmitter and subcarrier pooling and pool sharing functionality.

Fundamental PON simulation toolset will be formed and experimentally validated for scenario- relevant opto-electronic components, such as: dual-drive/dual parallel Mach Zehnder modulators, directly modulated lasers, IQ-modulators, (reflective) semiconductor optical amplifiers, electro-absorption modulators, injection-locked laser diodes, P-I-N and avalanche photodiodes. The platform will also include models for techno-economy, nonlinear transmission, pulse shaping, advanced modulation/multiplexing and mm-wave generation schemes. State of the art PON simulation toolset will thereafter be extended by including newly developed multi-flow SD transmitter modules designed for consideration of modular pooling approach, and related system level cost/performance evaluation models [32], [33]. Following previously established reference scenarios and requirements, in-house available link level simulation tools will be integrated with the PON toolset towards novel holistic model for joint consideration of OFH, BS5 femtocell and C-RAN paradigms. These paradigms will serve as use-cases for SDT design testing and identifying relevant heuristics for wireless-to-optical system repercussions. EXPLOR will also introduce optical transceiver modules based on cascading configurations of individual components for reduced cost/consumption, considering tandem designs based on various components. Tandem configurations will be designed to allow different functionalities on different cascading stages to maximize the level of coexistence between optical transmitter and subcarrier pools comprising the CS. We strongly anticipate that the aimed high level of optical pooling coexistence will result in increased reliance on low-cost components and decreased system redundancy.

PON toolset design will entail gradual evolution of system complexity and modular experimental assessment of each design stage, resulting in a number of candidate transceiver configurations. Said assessment will include numerical cost versus performance analysis, considering previously established 5G heuristics and requirements relating to C-RAN functional split and femto-cell designs. This will enable further refinement of the established requirement for the amount and type of individual components comprising the CS and address the efficiency of resource management.

D. Integration, Cognition and Adaptive Optimization

Each developed technology and toolset will be integrated into the EXPLOR platform. We will pursue inter-module feedback functionalities, designed to target custom latency versus accuracy optimization specific to a given use case. This includes stochastic geometry to system level simulation feedback functionality with the purpose of enabling proper identification of equivalent metrics (e.g. the worst case user) in regards to elected criteria (e.g. performance, latency) to ensure required accuracy at reduced computational latency. EXPLOR will also pursue innovative feedback mechanisms for improved resource management in a novel scenario via full-duplex communication between C-RAN and virtualized optical infrastructure, as two intelligent functional blocks performing resource management in cooperation. In this sense, EXPLOR will include network cognition functionalities unique to the project convergence scenario.

Network cognition and C-RAN paradigms have been introduced to 5G via software-defined networking and network function virtualization architectures, towards providing robust and efficient solutions within a flexible resource allocation and smart network management strategy [34]. For that reason, machine learning techniques have been examined in light of 5G mobile networks in order to enhance the efficiency of the network management as well as provide efficient solutions regarding security capabilities. Machine learning aims at algorithms and models towards real-data based decisions and without following pre-defined look-up tables.

Existing machine learning algorithms generally fall into three categories: supervised learning (SL), unsupervised learning (USL) and reinforcement learning (RL). More specifically, SL algorithms learn to conduct classification or regression tasks from labelled data, while USL algorithms focus on classifying the sample sets into different groups (i.e. clusters) with un-labelled data [35]. In RL, algorithms learn to find the best action series to maximize the cumulated reward (i.e. objective function) by interacting with the environment. The latest breakthroughs, including deep learning (DL), transfer learning and generative adversarial networks (GAN), also provide research and application directions with vast potential [36].

In EXPLOR, we will propose novel flexible resource allocation and smart network management strategy based on DL/GAN framework in network cognition and C-RAN. Proposed DL/GAN framework will be adopted for automation, self-awareness, and self-organization - targeting both physical layers and resource management procedures in optical and wireless models - in order to handle the enhanced complexity of EXPLOR platform management. The relevance
of this approach in the field is considerable, as it enables solving exceptionally complex scheduling tasks in real time even with a very modest processing capability. To enable and emulate such learning, however, information would have to be shared between network nodes and aggregated effectively, such that scheduling policies could be devised and applied. In addition, ML functionality enables the network to respond to changes in deployment, settings and environment. To that end, co-located 4G and (B)5G systems will be leveraged to improve one another’s performance. For instance, mm-wave 5G signal may provide better position estimate, improving 4G interference planning, while 4G may provide faster BS discovery. While advantages of doing so have been considered in the literature, very little practical work was done towards applying this approach to the converged optical-wireless scenario and enabling this functionality in an integrated simulation platform - which are the aims of EXPLOR project.

IV. PROJECT METHODOLOGIES

Reference scenarios based on market and SOTA technologies (NGPON2, NGEAPON, LTE/LTE-A/LTE-A Pro) will be defined first, focusing on converged optical wireless network scenario, radio resource availability, coexistence entailing infrastructure sharing and mm-wave frequencies compliant with projected femto-cell operation trends. A set of reference scenarios and use cases will be determined, focusing on beyond 5G deployment use cases, such as high mobility, beamforming and vertical deployment, among others. Numerous mm-wave generation, transmission and detection schemes will be included for comparison. These use cases will be considered in later stages to support the potential applications of the project outcomes. Positive and negative test cases will be defined for each requirement under consideration, formulated to include test category (e.g. computational latency, numerical accuracy, interoperability between individual modules, etc.), stage-by-stage requirements, and outcome. We will thereafter define both quantitative and qualitative performance metrics for each use case included. In the later stages, the performance evaluation of integrated EXPLOR platform will entail running those performance metrics against the previously defined test cases.

Candidate DFS architectures will be considered via mapping of coexistence network functional blocks to possible test hardware, and application of optimization methods to the mapping task using hardware-in-the-loop (USRP and SDR). The optimization of the architectural mapping will be enabled by considering simulation results and benchmarks based on LTE14/15, targeting performance bottlenecks and network flexibility across varying loads. Development of resource allocation procedures across multiple sites in a C-RAN setting will entail the collection of load data through mobility and clustering models, modelling of several test scenarios (e.g. a small town) and formalization of the resource mapping tasks and relevant limitations. Network modelling for SNR distribution at the system level within a cellular context will be, at first, dimensioned from a traditional 2D perspective, incorporating transmitter models that characterize the signal strength for multitter cellular layouts, as transmitter spatial structure plays a key role in evaluating mutual interference. These will be extended to 3D models as to account for more complex 5G deployment scenarios, including 3D beamforming, and modularly assessed using SL simulators. 5G modelling for complex deployment scenarios will enable characterization of SINR dynamics for a moving user relative to a single BS, as to model/optimize rate adaption, beam alignment and feedback for a given UE-BS pairing. Each optical SD transceiver configuration will be characterized in relation to their mm-wave frequency, cost, reach and capacity. These results will enable relevant compatibility and feasibility studies in fields that relate to low cost, virtualized OFH design, and allow relevant updates to the baseline requirements and lookup tables throughout remaining tasks, reflecting on the femto-cell and C-RAN architectures. OFH modules will be validated using PON experimental testbeds based on both wavelength division multiplexing (WDM) and optical frequency division multiplexing (OFDM), as well as the hybrid wireless-optical testbed - including interfaces for existing legacy systems with multiple protocol stacks for NG technologies as well as modular deployment and assessment of novel hardware/software solutions. The testbed will readily provide experimental characterization capabilities for beyond 50GHz mm-wave transmission and up to 110GHz in combination with external oscilloscopes.

Finally, the hybrid testbed will be used to demonstrate the effectiveness of the EXPLOR platform as a whole. A final EXPLOR demonstration event will be held to to provide a unique opportunity for bringing together relevant stakeholders, including the participation of industry players and networking equipment vendors to facilitate further knowledge sharing and encourage the early adoption of the project outcomes in industry products.

V. CONCLUSION

The EXPLOR project pursues the development of a comprehensive modular software with fully validated component and system level numerical models, cognitive and adaptive features, and use-case libraries targeting next generation converged optical wireless networks. The EXPLOR platform will be modelled to enable deep academic and techno-economic considerations of relevant beyond 5G features in an integrated manner, such as high end mm-Wave frequency, optical fronthaul, femto-cell based communications, network cognition and cloud-RAN environment functionalities. Interface and feedback functionalities designed to enable modular inclusion of external, user generated scripts and satisfactory latency versus accuracy trade-offs will be pursued. As such, the platform will act as an extensive enabler of future innovation targeting beyond 5G networks.

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