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5G Backhaul Challenges and Emerging Research Directions: A Survey

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ABSTRACT 5G is the next cellular generation and is expected to quench the growing thirst for taxing data rates and to enable the Internet of Things. Focused research and standardization work have been addressing the corresponding challenges from the radio perspective while employing advanced features, such as network densification, massive multiple-input-multiple-output antennae, coordinated multi-point processing, inter-cell interference mitigation techniques, carrier aggregation, and new spectrum exploration. Nevertheless, a new bottleneck has emerged: the backhaul. The ultra-dense and heavy traffic cells should be connected to the core network through the backhaul, often with extreme requirements in terms of capacity, latency, availability, energy, and cost efficiency. This pioneering survey explains the 5G backhaul paradigm, presents a critical analysis of legacy, cutting-edge solutions, and new trends in backhauling, and proposes a novel consolidated 5G backhaul framework. A new joint radio access and backhaul perspective is proposed for the evaluation of backhaul technologies which reinforces the belief that no single solution can solve the holistic 5G backhaul problem. This paper also reveals hidden advantages and shortcomings of backhaul solutions, which are not evident when backhaul technologies are inspected as an independent part of the 5G network. This survey is key in identifying essential catalysts that are believed to jointly pave the way to solving the beyond-2020 backhauling challenge. Lessons learned, unsolved challenges, and a new consolidated 5G backhaul vision are thus presented.

INDEX TERMS 5G, backhaul, fronthaul, small cells, heterogeneous network, C-RAN, SDN, SON, backhaul as a service.

I. INTRODUCTION

Societal changes, witnessed since the explosion of data services, and the growing appetite for wireless broadband have incentivised the speedy development of the fifth generation of cellular systems (5G), envisioned for year 2020 [1]. In order to cater for the anticipated 1000× capacity, key players foresee the need for a ''revolution'' in some aspects of legacy systems accompanied by enhancements in existing technologies [2]. Based on early consortiums in the development of 5G, promising enablers have been identified: ultra-dense networks (UDN), advanced inter-cell interference coordination (ICIC) schemes, massive multiple-input-multiple-output(MIMO) and coordinated multi-point processing (CoMP), centralised/cloud processing, and user/control plane decoupling. UDNs are often heterogeneous networks (HetNets), i.e., multi-layered including legacy high power macro-cells and very dense cells with lower power (small cells). Small cells are multi radio access technologies (multi-RAT) capable and represent an essential part of UDNs, which are considered an imperative 5G solution [3]–[8]. Sharing the spectrum in a UDN requires intelligent inter-cell interference coordination, cancellation or exploitation. Accordingly, key radio UDN facilitators have been developed: CoMP and enhanced ICIC (eICIC). The increasing need in processing power coupled with the emerging small cells diversity in traffic patterns, both spatial and temporal, render the concept of centralized radio access network (C-RAN) very attractive. C-RAN consists of splitting the functions of the traditional evolved Node B (eNB, i.e., the cellular radio station) and migrating them towards a distant shared pool of baseband resources, referred to as baseband unit (BBU). Basic radio functions remain at the radio site, hence the terminology remote radio unit (RRU). The C-RAN architecture capitalises on the diversity of traffic peaks, hence, improves the utilisation efficiency of the infrastructure. A the same time, it promotes the green aspect of 5G, owing to close the proximity of cells and users and corresponding lower transmission power requirements [9]. Another challenge resulting from UDNs is the user mobility management; traditionally, users moving from one cell to another require a handover procedure managed by the mobility management entity in the RAN. If this model were applied to UDNs, it would generate a crippling signalling overhead due to the limited footprints of small cells, hence frequent cell border crossing. Accordingly, splitting data and control planes is another essential 5G technology: small cells are used as data offloading points whereas mobility handover is triggered when users move between clusters as opposed to small cells [6], [10]. According to NTT DoCoMo, most of the presented enablers are either not new or not ''intelligent'' as stand-alone techniques, but consolidating them into a complete coordinated solution results in innovation, such as the advanced C-RAN [11]. Although such technologies can potentially address the greedy 5G capacity requirements and reduced RAN-related capital and operational expenditures (CapEX and OpEX), a new challenge has nonetheless emerged: the 5G backhaul.

The backhaul (otherwise referred to as back-net or backbone or transport network), in cellular networks, is the network that connects the eNBs to the core network and consists mostly of dedicated fibre, copper, microwave, and occasionally satellite links. In pre-LTE (Long term evolution) cellular generations, the radio controller node often acts as a backhaul aggregation point, thus, concentrating backhaul connections from all radio stations within its reach, towards the core. LTE's architecture does not employ a radio controller node, however, backhaul aggregation remains desirable for both wired and wireless connections, as shown in Figure 1. With the rise of C-RAN architecture, the 5G backhaul has evolved to a more complex network composed of *fronthaul*, *midhaul*, and *backhaul*. The backhaul section connecting the remote radio head (RRH) to the baseband unit (BBU) directly, or to an intermediate aggregation point, is labelled fronthaul. The basic fronthaul is assumed to run over a common public radio interface (CPRI) separating the RRH from the BBU. Due to the stringent requirements of the CPRI-based fronthaul, novel interfaces are being explored such as the fronthaul-lite [12], next-generation fronthaul interface (NGFI) [13], or xHaul [14]. In this paper, all forms of fronthaul are referred to as *fronthaul*. Based on the 3GPP terminology, the inter-eNB X2-based interface is called the midhaul [15]; the term has recently been used to refer to the group of links connecting the fronthaul aggregator to the backhaul aggregation point (see Figure 2). While the network connections between aggregation points and the core, based on the S1-interface [15], have retained the term backhaul. In this paper, we use the term backhaul to refer to the entire transport network including midhaul and fronthaul.

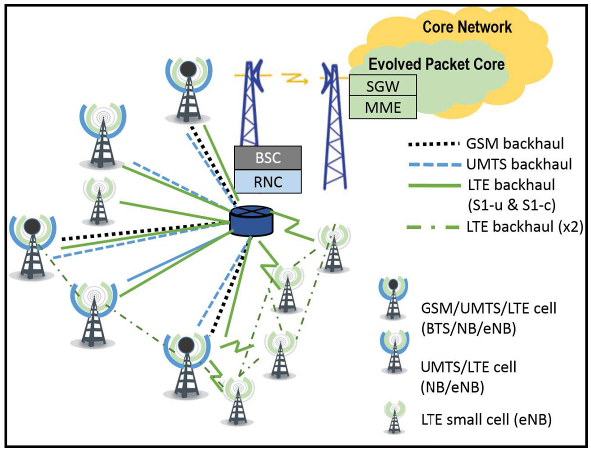

FIGURE 1. The GSM base station controller (BSC) and the UMTS radio network controller (RNC) are often co-located, and are used as backhaul aggregation points for BTS, Node B and eNB backhaul links. The eNB connects directly to the service gateway (SGW) for user data transmission over the S1-u and to the mobility management entity (MME) for control data transmission over the S1-c interface. In addition, inter-eNB interfaces, referred to as X2, are often routed through the aggregation point.

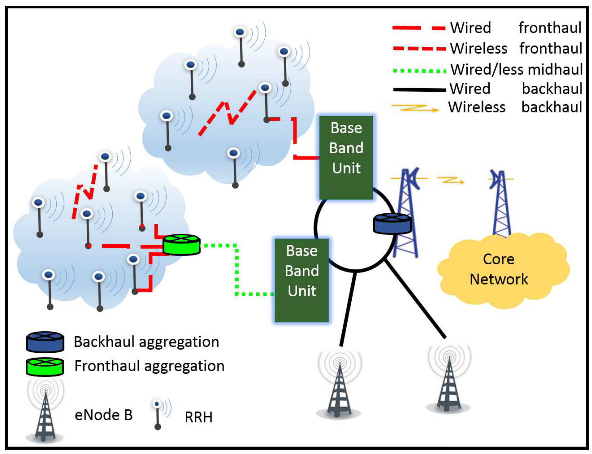

FIGURE 2. Example 5G network mobile backhaul network consisting of fronthaul, midhaul, and traditional backhaul. The fronthaul refers to the last mile transport links connecting the RRH to the network. The midhaul is the link between the fronthaul aggregation point and the backhaul network. The backhaul links are those that connect the BBUs to the network; the group of all transport links is also referred to as backhaul network.

Inhibitive bandwidths greater than 10 Gbps and maximum allowed latency in the orders of hundreds of microseconds, render fibre optics, perhaps the only fronthaul viable solution [6], [16]. However, laying fibre to connect all envisaged RRH to the core may be impossible in some cases and certainly very costly otherwise. In view of the immense challenge facing 5G deployment, the 5G backhaul research has been triggered, aiming at bridging the gap between the requirements stipulated by the 5G RAN and the realistic backhaul capabilities from two different perspectives. The first consists of evolving the current backhaul (microwave, optical fibre, copper, etc.) to meet 5G expectations and encompassing new wireless technologies such as in-band links (reuse the radio access spectrum), millimetre wave (mmWave), free space optical communications (FSO), and sub-6GHz (e.g. Worldwide Interoperability for Microwave Access-WiMAX, WiFi). The other backhaul research perspective looks at adapting the 5G RAN to the available backhaul with realistic performance, such as investigating intermediate RAN architectures between the C-RAN and the distributed RAN (D-RAN) to fit the fronthaul capabilities [12], [14], [17].

The evolutions of backhaul solutions from 2G to 3G and from 3G to 4G are well surveyed in [18] and [19], respectively. Also, [20] provides a comprehensive study of circuit switched and packet switched backhaul technologies as perceived in 2011, before the launch of LTE. However, to the best of our knowledge, there has been no comprehensive survey on 5G backhaul challenges and evolution in the literature. iJOIN[1] group, provides a representative review of backhaul evolution for UDNs and cloud-RAN within a broader context of RAN evolution. The backhaul review targets the physical level, medium access control and resource management level, and network level in three deliverables [21]–[23], respectively. Next Generation Mobile Networks (NGMN) provide a consensus around operators' views on UDN backhaul requirement with a focus on ''the last mile'' link to small cells [8]. The Small Cell Forum (SCF) builds on findings reported by NGMN, and presents accordingly a technical review on diverse UDN backhaul solutions and explores their suitability for identified use-cases [24]. These works, [8], [21]–[24], jointly provide an insightful starting point to grasping the problem of next generation's backhaul network and essential review on solutions portfolio.

In this work, we present the first comprehensive survey that explains the 5G backhaul problem, examines proposed solutions, and puts forward a set of tangible guidelines for adapting the backhaul solution to the various 5G scenarios whilst offering a consolidated vision of a dynamic, flexible and adaptive 5G backhaul framework. We first identify and quantify the 5G features with high impact on the backhaul performance. Then, the available backhaul solutions are categorised in terms of their respective nominal performance and limitations. The first contribution is a matching exercise between the required and available performance metric from the compiled data which sheds light on the impact of various RAN features on the restriction of backhaul choices, and vice-versa. Another contribution is the presented joint RAN/backhaul perspective to different combinations of possible RAN architectures and backhaul solutions, which offers a tangible tradeoff analysis between gains and losses incurred from each. The results from these studies help in delimiting the solution space and higher level requirements of the 5G backhaul solution: a heterogeneous network composed of various wired and wireless links with the ability to dynamically adjust and adapt to the changes in the network in a flexible, efficient, and timely manner. A comprehensive survey of backhaul state-of-the-art research is conducted highlighting key trends and how these can collaborate to form a holistic 5G backhaul solution. Thus, another contribution in this work is the consolidated 5G backhaul vision that we propose, referred to as backhaul as a service (BHaaS), which builds on key research findings such as software defined networks, heterogeneous backhaul technologies, joint RAN/backhaul operation, self-optimisation techniques and proactive caching to deliver the required backhaul flexibility and adaptability.

Any attempt to frame and survey the 5G backhaul problem should start with a pertinent definition of 5G networks. Accordingly, in Section II we first identify major 5G aspects that impact the backhaul network and proceed towards investigating related challenges and state-of-the-art solutions. Consequently, Section III presents legacy backhaul networks and discusses how 5G characteristics impact the backhaul and their corresponding requirement. Main research directions in backhaul technologies are classified in Section IV under six major categories: fibre-based, wireless, SDN-enabled, cache enabled, green efforts, and joint RAN-backhaul intelligence. Section V concludes the article with an outlook on foreseen challenges and research directions. Abbreviations and acronyms used are first introduced upon the their first occurrence in the text and are also tabulated in Table 9 for ease of reference.

II. A BACKHAUL 5G PERSPECTIVE

The 5G backhaul research topic exists as a consequence of the holistic 5G network ambitious challenge. To this end, 5G features that impact the backhaul ought to be first identified and studied, from a backhaul perspective, in order to delineate the 5G backhaul research topic. There is currently no complete standardised definition of 5G networks, however, a general direction of main goals is emerging through diverse group efforts and can possibly be summarised in this paragraph. The main 5G initiatives globally are: in the United States such as 4G America, in China e.g., IMT-2020 (5G) promotion group, in Japan e.g., 2020 and beyond, in Korea with the 5G forum, and in Europe, mainly, the 5G Private Public Partnership (5G PPP) funded by the European Union and the 5G Innovation Centre (5GIC) at the University of Surrey in the UK. Key examples of European projects researching technology beyond 4G can be found in [25]. The International Mobile Telecommunications system (IMT) has initiated research and technology trials in 2013 and plans to start the standardisation phase in 2016. The 2015 World Radiocommunication Conference identified chunks of mmWave spectrum bands, between 20 and 80GHz, for testing, but postponed the allocation of 5G spectrum till the next conference in 2019. It was also decided that the third generation partnership project (3GPP) will have a technical specification group (TSG) that will start the work on the 5G RAN in 2016 [26]. In addition, the International Telecommunication Union-Radio Communication Sector (ITU-R) working party 5D is responsible for the definition and

[1] Interworking and Joint Design of an Open Access and Backhaul Network Architecture for Small Cells based on Cloud Networks.

evaluation of 5G (IMT2020) networks; the plan is to deliver 5G specifications by October 2020 [27].

Ericsson, in a presentation on IMT-2020, state that 5G is about "making the extremes possible" [28]. Indeed, the IMT vision as summarised by METIS,[2] targets 1000× capacity increase, 10-100 more connected devices, compared to today's cellular performance, data rates in the order of Gbps and sub-millisecond latency, at the cost and energy consumption of current networks [29], [30]. These requirements impact the backhaul directly which should bear a data explosion at minimum delay and cost with high resilience and green considerations. Such ambitious expectations are perhaps unrealistic and impossible to realise holistically; nonetheless, the dominant 5G feature that the backhaul needs to capitalise on is the diversity of requirements. For example, latency in smart meter applications could stretch to tens of minutes, or more, whereas tactile internet requires end-to-end values less than 1 msec. Similarly, real-time video applications would require extremely high data rates, whereas fleet management transmits and receives at low data rates. In addition, 5G should provide the platform to connect a massive number of objects to the internet, thus, supporting the Internet of Things. Smartphones and devices (e.g., smart meters), however, differ greatly in their processing power, radio components, and battery capabilities. Smart meters need to be low-cost devices with very long battery life (up to 10 years), thus, energy efficiency in communication is crucial for this application; while, video conferencing, for instance, would have latency and throughput, instead of energy efficiency, as a priority target. A detailed listing of typical 5G user experience and system performance requirements is available in [31], showing data rates varying from 1 kbps to 1 Gbps and latency from microseconds to hours. Such heterogeneity in service expectations reflects on the backhaul requirements. Accordingly, a 5G backhaul should not necessarily be holistically compliant with the most stringent specifications; instead, it should be flexible and adaptive in such a way that all services are catered for in an efficient manner while conforming with their attributes.

In order to provision for the increase in capacity, devices, and data rates, efforts are invested in three axes jointly: network densification, improved spectrum efficiency, and spectrum extension [16]. The features employed towards these ends are partly an evolution of existing technologies (e.g., HetNets, CoMP, massive MIMO) and partly disruptive to state-of-the-art cellular systems (e.g., C-RAN and control/user plane split). In Sections II-A and II-B, we discuss key evolved and disruptive 5G features, respectively, from a backhaul perspective. For a recent comprehensive review on 5G technology and converging trends, please refer to [25].

A. EVOLVED 5G FEATURES

5G technology trends include the evolution of existing features such as carrier aggregation, MIMO, CoMP, and HetNets, which have already been standardised for LTE/LTE-A and have shown promising gains in boosting the number of connected devices and corresponding data rates. Carrier aggregation is introduced in release 10 of LTE and further extended in release 11. It basically consists of equipping a cell with more than one carrier components (total maximum bandwidth up to 100 MHz) with joint scheduling, hence, reaching users with higher data rates. Release 13 is expected to support aggregation of 32 carrier components, hence, larger aggregate bandwidth [32]. The aggregate radio throughput of a cell scales with the available radio bandwidth, thus, may necessitate larger capacity on the connecting backhaul link.

MIMO is based on spatial multiplexing, in which data streams from several branches are multiplexed and transmitted over several spatially separated channels. MIMO is an essential feature in LTE-Advanced; R10 transmission modes allow 4×4 MIMO for the uplink and 8×8 MIMO for the downlink. NTT DoCoMo demonstrated, in December 2012 10 Gbps using 8×16 MIMO with 400 MHz bandwidth, later showed simulated data rate of 30 Gbps using 24×24 MIMO [33], [34]. Massive MIMO is, thus, a prime enabler of 5G due to its data rate boosting capability. Network MIMO is a class of transceiver techniques, where the transmission and reception of signals, among multiple spatially distributed *base stations*, are coordinated so that interference is mitigated [35]. Network MIMO is often referred to as coordinated multi-point processing or CoMP. NGMN foresee a pivot role for massive MIMO and CoMP in ameliorating quality, fairness, and overall system efficiency [31]. Considering the variety of different CoMP methods already proposed for LTE, ranging from coordinated scheduling to joint transmission, 5G is expected to natively support the most effective techniques. However, both massive MIMO and CoMP transmission rely on the availability of timely channel state information, hence, would necessitate very low backhaul latency to realize their full potential. Moreover, these features often require that the user data be present (transmitted and/or received) in all cells in the CoMP cluster, consequently, the connecting backhaul links of those cells would have to be equipped with higher bandwidth to cater for the data of all users in the cluster (as opposed to users served by the cell alone).

HetNets also stem from the evolution of existing technology, which consists of various cell layers (e.g., macro-cell, micro-cell, pico-cell, etc.) and various radio access technologies (e.g., GSM, 3G, LTE, WiFi, etc.). They are considered an indisputable part of future cellular networks and have received a focused attention from 3GPP standardisation work [36]. Small cells may have different sizes, may be indoor or outdoor, and may be operator-planned or not (e.g., femtocells, low power cellular access points connected to the internet), but their common characteristic is that they are low power nodes at low heights used for data offloading [37]. Foreseeable UDN small cell density in highly populated areas may well reach 1500 cells per km^2,

[2]Mobile and Wireless Communications Enablers for the Twenty-Twenty Information Society.

including femtocells. HetNets maximise area spectral efficiency, due to the tight reuse of the precious spectrum, and economise on transmit power requirements, owing to the proximity of transmitters and receivers, thus, endorsing the "green" aspect of 5G. Advantages of small cells spring from these characteristics which allow high area spectral efficiency, and low uplink and downlink power, thus, long UE battery life and greener communications. When small cells are part of a HetNet, they may share the spectrum with the macro-layer (radio network layer formed by a group of macro-cells), a desired feature to maximise the usage of the spectrum. In this case, however, a cell association (or handover) problem arises since the cell selection is traditionally based on the strength of signals received from the candidate cells. The macro-cell is a high power station, thus, often reaches the users with higher signal strengths than small cells. The cell range extension feature was recently defined for HetNets to bias the small cells signals for attracting more users (e.g., [38]). With this feature, enhanced inter-cell-interference coordination (ICIC) schemes are used to limit the interference caused by the macro-cell to the small cells' UEs. In LTE release nine, ICIC was first introduced to exchange load and interference information over X2 (LTE interface between base stations). The base station would then consider received information to optimise scheduling, mostly targeting edge users [39]. With the emergence of HetNets, enhanced ICIC (eICIC) is defined in release 10, in which almost blank sub-frames are used on the macro-layer to reduce downlink interference on UEs associated with small cells [40], [41]. LTE release 11 includes further enhanced ICIC (feICIC), which aims at handling interference by the UE through inter-cell interference cancellation for control signals, enabling even further cell range extension [42]. With these features in place, small cells in ultra-dense HetNets are able to absorb the anticipated 5G massive traffic and an invasive number of devices. The capillaries of the backhaul network need to expand at the same pace and breadth as the small cell growth while providing higher throughput and lower latency, a staggering target on its own.

B. DISRUPTIVE 5G FEATURES

UDNs imply an invasive spread of small cells at a high cost of RAN equipment, even if the exorbitant cost of backhaul links is excluded. In addition, the limited coverage of small cells results in a large peak-to-average ratio of traffic demand, which would necessitate large allocation of baseband resources per cell if the traditional, or distributed, RAN (D-RAN) approach were adopted. The C-RAN aims at addressing both of these problems by reducing the complexity (hence cost) of small cells and pooling baseband resource, thus, improving their utilisation efficiency, irrelevant of the individual cell traffic patterns.

The "C" in C-RAN often stands for centralised or cloud but also clean and cooperative RAN. The focal concept is to redistribute functions, which are traditionally found in base stations, towards a cloud-operated central processor. Such centralised intelligence would consequently enable cooperative operation among cells for greener and cleaner (i.e., less carbon emissions) communication. A fully centralised RAN consists of taking most of the base stations functionalities away from the eNB and leaving only the radio functions at the remote radio unit (RRU) or RRH. Consequently, BBU, which is traditionally located in the base station cabinet, is relocated to the cloud or central processor, hence, forming a shared pool to all connected RRHs. With the C-RAN architecture, the LTE eNB is migrating towards the virtual eNB (VeNB), referring to the joint functionalities of the BBU and RRH that are in different locations [9].

In fact, a similar architecture has been deployed, as early as the second generation (2G) of cellular networks (e.g., GSM), for indoor coverage such as airports, shopping malls, and corporate building, called the distributed antenna systems (DAS). It consists of breaking the traditional 2G radio site, called base transceiver station (BTS), into two parts: the BBU and a set of RRHs. These two parts are normally connected with optic fibre links inside the radio cabinet, thus, the solution requires removing and distributing the RRH by prolonging the fibre connection using radio over fibre transmission. Consequently, spreading diligently these RRHs around a building provides a continuous and close-to-uniform indoor coverage, irrespective of the traffic distribution. DAS may be considered as an implementation option of C-RAN in which quantised signals are exchanged among the RRHs to enable centralised or de-centralised joint decoding, as described in [43] and [44]. C-RAN is thus an evolution of DAS which introduces the novel concept of cloud BBU, whereby various BBUs may be located in different geographical areas while forming a cloud and connecting to more than on DAS. However, with the C-RAN architecture, the covered distances between RRH and BBU are larger than indoor solutions, and fibre is a luxury that is often unavailable. The fully centralised C-RAN, also referred to as baseline C-RAN configuration, consists of migrating the processing functions of layers one, two and three to the central processor, and leaving the basic function of analogue/digital conversion to the RRH. However, the resulting CPRI-based fronthaul requirements, in such a configuration, become overwhelming and, worse, independent of the actual traffic load in the RRH. Indeed, the CPRI-based C-RAN migrates both cell and user functions to the BBU, thus burdening the fronthaul with full-load even when no users are served by the BBH. Moreover, the MIMO-related functions are also migrated to the BBU resulting in a fronthaul traffic that scales with the number of MIMO antennae [14], [45].

Consequently, the level at which the traditional base station functions should be split, has become a prime research topic, termed *functional split*, which aims at finding an ideal split, by analysing the impact of different options on possible gains and fronthaul exigence. Most of the work in this domain has been conducted through iJOIN and has resulted in essential quantification of latency and capacity requirements imposed on the fronthaul, for different eNB breaking points [17].

Moreover, the impact of the functional split of CoMP and xICIC gains was also analysed by the same group (e.g., [9]) with the identification of implementation key challenges. The ultimate joint message from these works promotes a flexible and dynamic functional split orchestrated by the cloud, since all research show that there is no one-solution-fits-all in this area [45]. Another interesting work, [46], agrees on the need of various splits for different scenarios and categorises different split levels with respect to achievable gains and cost imposed on the backhaul network (as a function of the bandwidth and latency required). iJOIN endorse the concept of flexible cooperative processing through their RAN as a service, RANaaS. The RANaaS enables coordination between cells, thus, interference mitigation, intelligent spectrum utilisation, and energy efficiency in cellular communication [21]. C-RAN architecture is a leading solution towards economising on the capital expenditure by using low-cost RRH and pool sharing expensive BBU. Moreover, data rate boosting radio features such as xICIC, massive MIMO, and CoMP require tight and fast coordination between various cells, hence, would benefit from centralised processing.

However, the C-RAN has also disrupted the backhaul network architecture and created a new type of links, that is a hybrid between RAN and backhaul: the fronthaul. These links connect essential parts of the virtual eNB, thus can be considered as RAN parts, but they can also be seen as extensions to the backhaul. Moreover, the C-RAN and corresponding fronthaul can only be designed jointly to ensure coordinated performance over the virtual eNB, hence, a disruption to the traditional network design is also incurred. In other words, the functional split can only be decided based on the available fronthaul solutions, and the required fronthaul performance can only be stipulated by determining the level of RAN centralisation. Diverse efforts in the industry are leading towards the convergence of using the common Ethernet packet backhaul for the fronthaul, motivated by the advantages of ease of deployment, inter-operability, and cost, e.g., [13]. Delay and loss of synchronization remain challenges for a the adoption of Ethernet in the fronthaul and are currently being addressed by the iCIRRUS[3] project [12].

Another network architectural revolution is the decoupling of the user data and control plane; a need fuelled by the intrinsically restricted footprint of small cells in a UDN. Mobile users would be crossing cell borders very often in a UDN, thus, generating a debilitating signalling load from handovers and cell reselections. By separating the user data and control planes, handovers and reselections are required when the user moves between anchor cells only; these are macro-cells that cater for the control plane while the data plane is tunnelled through various small cells within the macro-cell coverage. The concept of control/user plane split is often referred to as soft cell or phantom cell. Such a split was envisioned for release 12 of LTE but has recently been moved to release 13 [32], [47]. System information is broadcast over the anchor cell which also manages most of the radio resource control and signalling, while the small cells play an assistant role, having data offload as a main task [48]. Furthermore, a decoupling of uplink and downlink connection points is also suggested to enable greener and cleaner communication by selecting the network layer (i.e., small cell or macro-cell) that requires least transmit power [49]. The soft cell concept is strongly endorsed by key 5G pioneers such as NTT DoCoMo [10], iJOIN [6], and MiWEBA[4] [50].

C-RAN, control/plane split, and decoupling of uplink and downlink all necessitate very low latency on the backhaul to ensure coordination and timely synchronisation among pertinent parallel channels. In addition, the C-RAN architecture inflates the effective backhaul throughput such that links suitable for an eNB deployment act as a funnel for a VeNB, under the same user traffic load.

III. EVOLUTION TO 5G CELLULAR BACKHAUL NETWORK

5G targets are evidently ambitious and intensify the design challenges of the backhaul. This section presents a technical appraisal of backhaul technologies followed by quantified 5G requirements in order to assess the pertinent performance gaps and shed light on the possible solutions. To this end, a summary of existing and emerging backhaul technologies' performance is first compiled, taken from various key sources. Different 5G deployment use-cases are then considered employing C-RAN and CoMP, since both features affect the stipulated backhaul performance. SCF states that "the backhaul is NOT a barrier to small cell deployment" given the large available backhaul toolbox and the diversity of small cell use-cases [24]. Accordingly, we present a quantitative and representative set of tailored 5G backhaul solutions for various deployment scenarios.

A. BACKHAUL TECHNOLOGIES

There are many documents that describe the growing portfolio of backhaul/fronthaul solutions including legacy and novel technologies such as [18]–[21] and [24]. Key information pertinent to this survey is summarised in Tables 1 and 2 for wireless and wired solutions, respectively. For more details on a specific topic, readers are invited to refer the corresponding cited documents in the tables.

Current backhaul networks are mostly built with microwave links (often operator owned) and fibre/copper-based links (often leased) with different proportions per operator and country [51]. A study conducted in 2014 brings attention to the fact that optic fibre backhaul is not available nationwide in Europe and that current microwave replacements cannot sustain the traffic growth of LTE/LTE-A beyond 2017-2018 [52]. Indeed, fibre to the home (FTTH) is scarce worldwide with only 16 countries exceeding 15% FTTH penetration [53]. The need for innovation in backhaul provisioning is thus evident and becomes more vital in the dawn

[3]iCIRRUS (intelligent Converged network consolidating Radio and optical access aRound USer equipment) is an EU Horizon 2020 project.

[4]MiWEBA - Millimetre-Wave Evolution for Backhaul and Access.

TABLE 1. Wireless backhaul technical solutions.

Technology	Options	Upstream throughput	Downstream throughput	Latency/ Jitter	Distance	Note
Microwave PtP †	PtP	1 Gbps	1 Gbps	< 1 msec/ hop	2-4 km	6-60 GHz remote not-spot
Microwave PtmP †	PtmP	1 Gbps	1 Gbps	< 1 msec/hop	2-4 km	6-60 GHz peppered capacity
Satellite †	LOS	15 Mbps	50 Mbps	300 msec one-way latency 5-30 msec jitter	~ubiquitous	due to cost per Mbps realistic Tput 2-10 Mbps DL/1-2 Mbps UL
TVWS †	NLOS	18 Mbps/ch	18 Mbps/ch	10 msec	1-5 km	up to 4 channels up to 10 km at 10 Mbps using 2 ch with LOS
mmWave 60 GHz †	LOS	1G bps	1 Gbps	200μ sec	1 km	scalable
mmWave 70-80 GHz †	LOS	10 Gbps	10 Gbps	65-350μ sec	3 km	scalable
Sub-6GHz 800 MHz-6 GHz †	NLOS	170 Mbps	170 Mbps	5 msec single hop one way	1.5-2.5 km urban 10 km rural	licensed (20 MHz TDD) expected to increase to 400 Mbps
Sub-6 GHz 2.4, 3.5, 5 GHz †	NLOS	150-450 Mbps	150-450 Mbps	2-20 msec	250 m	unlicensed data rate depends on MIMO
FSO ‡	LOS	10 Gbps	10 Gbps	low	1-3 km	

† Refer to [24].

‡ Refer to [54].

of 5G; to this end, a compilation of available and potential technologies is presented here.

Any of the listed backhaul technologies could be deployed in different topologies that would, in turn, impact the nominal performance in Tables 1 and 2. Point-to-point (PtP) links could be mounted in chain, tree, ring or mesh networks, for instance, but the incurred delay will increase with link length, the number of hops, and delay in aggregation/demultiplexing points. Point-to-multi-point (PtmP) architectures, on the other hand, curtail the dependency of the backhaul network performance on the number of aggregation nodes while enabling easy addition/deletion/modification of nodes. In the presence of C-RAN and pooled BBU, PtmP becomes a favourable architecture for the mobile fronthaul.

B. 5G BACKHAUL REQUIREMENTS

Evidently, the mobile backhaul/midhaul/fronthaul network is an essential milestone towards realising a 5G network. It is clear that more capacity, less latency, synchronisation, security, and resilience are needed. However, it is a prerequisite to quantify the required improvements in an attempt to identify the optimum solution (or set of solutions) from the listed options in Tables 1 and 2. SCF defines four main use-cases for small cell deployments: capacity hotspot, peppered capacity for quality of experience (QoE) boost, outdoor not-spot, and indoor not-spot as listed in Table 3.

Each of the use-cases has different requirements in terms of capacity, latency, resilience, and others. For each of these use-cases, different RAN architectures could be deployed, starting with the traditional D-RAN and different levels of function centralisation. We consider five different functional splits, as depicted in Figure 3; corresponding backhaul requirements for a simple deployment of LTE-FDD assuming 20 MHz bandwidth, two receive antennae, and 50% cell load are listed in Table 4. A key aspect is that the backhaul bandwidth requirement scales with larger radio access bandwidth and becomes crippling with $\geq$100 MHz possible 5G allocations per small cell. It should be highlighted that Split A depicts the baseline C-RAN architecture whereby the RRH and the BBU are connected over a CPRI interface. The round trip time over the CRPI interface is 5 μsec and the effective admissive delay over the fronthaul link, including propagation delay is in the order of 100 μsec. Moreover, Split-A has the most exigent throughput requirement over the fronthaul, even when the actual user traffic is minimum (or null). All split options above Split-A scale with the actual traffic, hence, allow exploiting the statistical multiplexing gain based on occupied physical resources. Moreover, the backhaul throughput requirement becomes flexible and more relaxed since it depends on the actual user throughput related to the user channel quality. On the other hand, latency requirements remain critical and are determined by the channel coherence time, hence, the user speed of movement. In these functional splits, latency requirements are governed by the hybrid automatic repeat request (HARQ), link adaptation, and scheduling processes. Opportunistic HARQ is proposed in [59], which divides the HARQ process into a time-critical part conducted at the RRH and computationally intense part that takes place at the BBU; such an approach relaxes

TABLE 2. Wired backhaul technical solutions.

Technology	Options	Upstream throughput	Downstream throughput	Latency/ Jitter	Distance	Note	Ref
Fibre PtP	PtP	≥10 Gbps	≥10 Gbps	<1 msec	~20 km		[24]
PON/VDSL2	FTTC	10-50 Mbps	80-100 Mbps	3.8-11.8 msec one way	<1 km copper length		[24]
GPON	FTTP	1.24 Gbps	2.5 Gbps	1-7 msec	up to 29 km		[24]
NGPON	FTTP	2.5 Gbps	5 Gbps	1-7 msec	up to 29 km		[24]
EPON	FTTP	1 Gbps	1 Gbps	1-7 msec	N/A		[24]
10G-EPON	FTTP	1 Gbps	10 Gbps	1-7 msec	N/A		[24]
VDSL2		15 Mbps	75 Mbps	5-15 msec one way	1 km	capacity is up to 100/20 Mbps (DS/US)§at <600 m	[24]
VDSL2 ph2		20 Mbps	100 Mbps	3 msec†	1.5 km	phantom mode; 2 pair bonding	[55]
VDSL2 ph4		40 Mbps	230 Mbps	3 msec †	1.5 km	phantom mode; 4 pair bonding	[55]
VDSL2 ph8		150 Mbps	750 Mbps	3 msec†	1.5 km	phantom mode; 8 pair bonding	[55]
G.FAST 50 m	50 m	1 Gbps‡	1 Gbps ‡	<1 msec‡	50 m	the data rate shown is US/DS aggregate	[56] [57]
G.FAST 100 m	100 m	500 Mbps‡	500 Mbps ‡	<1 msec‡	100 m	the data rate shown is US/DS aggregate	[56] [57]
G.FAST 200 m	200 m	200 Mbps‡	200 Mbps‡	<1 msec ‡	200 m	the data rate shown is US/DS aggregate	[56] [57]
DOCSIS 3.0		108 Mbps	304 Mbps	10-20 msec	1.5 km	8 channels for downstream; 4 channels for upstream	[58]
DOCSIS 3.1		1 Gbps	5-10 Gbps	N/A	N/A		[58]
EuroDOCSIS	3.0	108 Mbps	400 Mbps	10-20 msec	1.5 km	8 channels for downstream; 4 channels for upstream	[58]

§ US= Upstream and DS= Downstream.

† Realistic latency in the order of 10 msec.

‡ These are theoretical values; however, realistic throughput may be sub-1 Gbps and latency closer to 10 msec due to the error correction induced delay. Moreover, G.fast is a TDD technology thus the throughput quoted assumes full occupation of either upstream or downstream.

TABLE 3. Small cell forum use-cases [24].

Use-case	Capacity hotspot	Peppered capacity	Outdoor not spot	Indoor not spot
Inter cell coordination	yes	yes	no	no
CoMP	possibly	possibly	unlikely	unlikely
Frequency synch	yes	yes	yes	yes
Phase synch	yes	yes	no	no
Availability	99-99.9%	99-99.9%	99.9-99.99%	99.9-99.99%
BH Capacity	should not be limiting	should not be limiting	relaxed	relaxed
Estimated distance†	<1 km	<1 km	1-5 km	<1 km
Distance	to hotspot	flexible	to not spot	to building
GNSS available	likely	likely	likely	unlikely

† Distances are practical estimates, not defined in [24].

the latency requirements over the backhaul, as highlighted in Table 4.

In addition, for each use-case coupled with an RAN architecture, different CoMP techniques may be employed. Three levels of downlink coordination and two levels of uplink coordination are considered, as described in Table 5. A deployment scenario is defined by selecting an option from each of Tables 3 and 4, and choosing an UL and DL COMP option from Table 5. Consequently, The combination set is $4 \cdot 5 \cdot 3 \cdot 2 = 120$ deployment options with varying backhaul requirements, hence, different tailored solution. It should be highlighted, that the mentioned 120 possible deployments are only a subset of all actual possibilities since they do not include other optional features such as aggregate

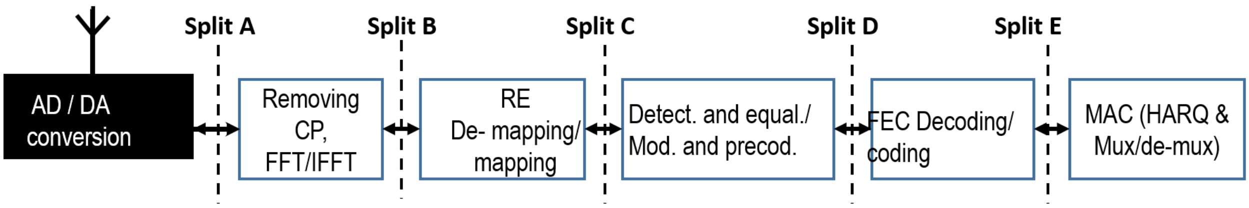

FIGURE 3. Functional split points considered (UL/DL) [17]. AD: Analogue to Digital; DA: Digital to analogue, CP: Cyclic prefix, FFT: Fast fourier transform; IFFT: inverse FFT, RE: Resource element, FEC: Forward error correction.

TABLE 4. Backhaul requirements for C-RAN and functional split options (see Figure 3) [46].

Option	Throughput	Latency
Split A- CPRI - I/Q forwarding	2457 Mbps	150 μ sec
Split B- Subframe forwarding	720 Mbps	150 μ sec†
Split C- Rx Data forwarding	360 Mbps	150 μ sec†
Split D- Soft bit forwarding	180 Mbps	150 μ sec‡
Split E- MAC forwarding	27 Mbps	~10 msec

Scenario considered assumes LTE-FDD 20 MHz bandwidth, 2 receive antennae, and 50% cell load (refer to [17] for full details).
† For slow-moving users and with opportunistic HARQ the latency requirement can be relaxed to 4 msec [59].

‡ For slow-moving users the latency requirement can be relaxed to 1-4 msec at the risk of higher probability of block errors.

TABLE 5. Backhaul extra capacity requirements for different forms of CoMP and C-RAN [46].

	Option	Split A§	Split B§	Split C§	Split D§	Split E§	D-RAN
DL	Joint transmission†	0	200 Mbps	200 Mbps	200 Mbps	200 Mbps	200 Mbps
DL	Coordinated beamforming†	0	0	0	0	0	N*1
DL	Coordinated scheduling†	0	0	0	0	0	N*1
UL	Coordinated scheduling‡	0	250 Mbps	250 Mbps	250 Mbps	0	N*1
UL	Joint reception/ MUD‡	0	250 Mbps	250 Mbps	250 Mbps	N*100	N*100

§ Centralised functional splits from Table IV.
† = Downlink; [‡]=Uplink.
N is the number of cells in the CoMP cluster.

Scenario considered assumes LTE-FDD DL, 2 receive antennae, 20 MHz 10 users in 64 QAM (peak), and 50% cell load.

radio bandwidth, MIMO size, cluster size, data compression, etc. Accordingly, 5G deployment alternatives are numerous; and with each, come different backhaul requirements and a corresponding tailored set of suitable backhaul solutions.

C. TAILORED 5G BACKHAUL SOLUTIONS

By considering the limited options listed in Tables 3, 4, and 5, it is possible to combine 120 different deployment options. In reality, the required backhaul bandwidth, in a C-RAN architecture, depends also on many factors such as aggregate carrier bandwidth, cell load, the number of sectors, modulation and coding scheme, the number of antennae, and others. In this paper, we consider a basic set of parameters, consisting of 20 MHz bandwidth, LTE FDD technology, 64 quadrature amplitude modulation, two receive antennae, and a cell load of 50% (i.e., half of resource blocks are occupied). Moreover, a CoMP cluster size of seven cells is considered. Accordingly, we select the peppered capacity use-case from Table 3, and corresponding backhaul requirements of all $5 \cdot 3 \cdot 2 = 30$ (five splits, three DL CoMP, and two UL CoMP) possible RAN/CoMP combinations, to all the listed backhaul solutions in I and II. The results are shown in Table 6.

We would like to emphasise, at this stage, that the data presented in Table 6 is a compilation from diverse sources as mentioned in the previous section, and the reader is referred to these sources as listed in Tables 1, 2, 3-A, 3, 4, and 5 for more details. However, the information provided is added value, because it consolidates key findings from different research into a practical guide that could help in creating a tangible vision of possible 5G deployment options, and identifying areas that require further research and improvement.

Looking at results in Table 6, it is clear that moving the functional split towards the medium access control (MAC) layer relaxes both latency and bandwidth requirements, thus, allows a larger backhaul toolbox and vice-versa. Notably, dark fibre is the only wired backhaul solution that conforms with baseline C-RAN configuration requirements, while mmWave and FSO are the only wireless possibilities. Another interesting point, inferred from Table 6, is that the functional split is more dominant in limiting the choice of backhaul solutions than the CoMP features. Actually, the only apparent impact of CoMP on backhaul selection is found with the MAC data functional split (Split E), in which joint reception and transmission limits the backhaul toolbox further compared to coordinated scheduling and beamforming.

The backhaul throughput requirements of all functional splits above Split-A scale with the traffic load; consequently, one can capitalise on tailored usage of the rich backhaul

TABLE 6. Possible backhaul solutions for the peppered capacity use-case.

Functional split	UL CoMP ‡	DL CoMP ‡	Possible backhaul/fronthaul solutions
Split A - CPRI-I/Q forwarding	JR or CS	JT or CB or CS	Fibre point to point† N-GPON mmWave 70-80 MHz† FSO†
Split B- Subframe forwarding	JR or CS	JT or CB or CS	Fibre point to point xPON† G-fast (up to 50 m)† DOCSIS 3.1 mmWave 60 MHz and 70-80 MHz† FSO†
Split C- RX Data forwarding	JR or CS	JT or CB or CS	Fibre point to point xPON† G-fast (up to 50 m)† DOCSIS 3.1 microwave (PtP, PtmP)† mmWave 60 MHz and 70-80 MHz† FSO†
Split D- Soft bit forwarding	JR or CS	JT or CB or CS	Fibre point to point xPON† G-fast (up to 100m)† DOCSIS 3.1 microwave (PtP, PtmP)† mmWave 60 MHz and 70-80 MHz† Sub-6GHz 2.4, 3.5, 5 GHz FSO†
Split E- MAC data	JR	JT	Fibre point to point xPON† VDSL2 with 8 pair bonding† G-fast (up to 200 m)† DOCSIS 3.0, 3.1 and EuroDOCSIS 3.0 microwave (PtP, PtmP)† mmWave 60 MHz and 70-80 MHz† Sub-6GHz 2.4, 3.5, 5 GHz FSO†
	CS	CB or CS	same as JR and JT VDSL2 with 4 pair bonding† Sub-6GHz 800 MHz-6 GHz TVWS (with 2 channels)

‡ JR is joint reception, JT is joint transmission, CS is coordinated scheduling, CB is coordinated beamforming.

† Backhaul technologies marked with †indicate that they conform with both throughput and latency requirements. Otherwise, the technology only accommodates the throughput requirements but is under-performing in terms of latency.

technology toolbox available. On the other hand, latency requirements are more crippling, inasmuch that RAN centralisation (below Split-E) is only possible in areas with restricted user movement or where dark fibre is available, due to stringent sub-msec latency needs. A recent work by Bartlet et al. advocates the importance of converged fronthaul and backhaul and a flexible functional split that adapts to the available backhaul links [60]. The authors also provide a comparative study between common (but not exhaustive) toolbox of backhaul technologies and C-RAN requirements, which complies with our findings in Table 6.

D. JOINT BACKHAUL/RAN PERSPECTIVE ON THE TRADEOFF BETWEEN C-RAN GAIN AND FRONTHAUL COST

C-RAN is presented as a key disruptive technology, vital to the realisation of 5G networks. However, based on Table 6, C-RAN-Split A is only feasible with direct optical fibre as a wired solution. In this case, how would 5G evolve in the absence of fibre, knowing that only five countries in Europe have more than 15% coverage of fibre to the home [53]? Wireless CPRI-fronthaul (e.g., mmWave) is another promising way forward, however, propagation challenges and incurred resilience issues are still partially unsolved and require more research to provide a mature reliable fronthaul solution. On the other hand, D-RAN is less demanding on the backhaul but is believed to lack in performance in terms of resource usage and efficiency of RAN deployment. Under such constraints, it is crucial to identify the most suitable architecture from a joint backhaul/RAN perspective.

The C-RAN versus D-RAN comparison has been addressed qualitatively in the literature, whereas it requires a quantitative analysis to enable tangible guidelines for this dilemma. Studies that advocate C-RAN for its superior RAN functionality and significant RAN cost reduction emphasise that it is only feasible with a fibre-based fronthaul; nonetheless, the latter is often unavailable and very expensive and impractical to deploy. On the other hand, there are studies that promote D-RAN because it operates over a realistic backhaul, but warns against losing the centralisation benefits (cost reduction and ease of deploying RAN features).

TABLE 7. Comparison between D-RAN and C-RAN architectures [61].

Factor	D-RAN	C-RAN
Cost of RRH / small cell	High	Low
Planning, deployment, maintenance of RRH / small cell	High	Low
Energy efficiency of RRH / small cell	Low†	High
Cost of BBU	N/A	High
Planning, deployment, maintenance of BBU	N/A	Low
Energy efficiency of BBU	N/A	High†
Potential for resource pooling	Limited	High
Fronthaul requirements	Relaxed	Exigent
Cost of backhaul/fronthaul‡	High	Higher
Level of inter-cell coordination	Limited	Maximum

†On/Off switching in a D-RAN architecture may be used to economise on energy consumption, but due to the complexity of the small cell, each would require additional energy for cooling and environment control and would still consume more energy when it is ON. The C-RAN RRH has low complexity, hence, is more robust and requires less energy to operate.
‡The cost of the backhaul in a D-RAN architecture is high in view of the additional capillaries needed to connect all cells to the backbone. For the same scenario the cost of the fronthaul is higher as a result of higher exigence, thus the need for more bandwidth, less latency, resilience, etc.

Various functional splits are also analysed from a fronthaul perspective and resulting reduction in overhead, while highlighting the increase in RRH complexity and the incurred limitation in RAN features. Table 7 summarises the general messages from the C-RAN/D-RAN comparison. The gap in these studies is a quantitative comparison of how much is lost and how much is gained with the various RAN architectures when looking at the problem from a joint backhaul-RAN perspective.

In this section, we present a cost-versus-benefit analysis of different functional splits, considering three types of backhaul technologies: copper-based G.fast, point-to-multi-point microwave, and optical fibre based GPON (see Figures 4, 5, 6). The study takes on a joint backhaul-RAN perspective and is based on a holistic network dimensioning method using backhaul-aware dynamic cell range extension approach; more details can be found in [61]. The difficulty in this analysis stems from tagging a realistic relative cost to each of the advantages and disadvantages listed in Table 7.

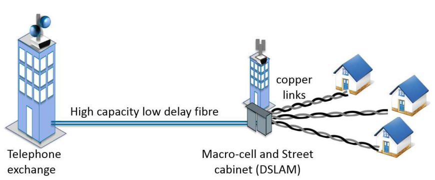

FIGURE 4. Last mile of the small cell backhaul employs copper-based G.fast.

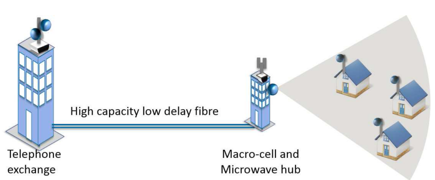

FIGURE 5. Last mile of the small cell backhaul is provisioned using is PtmP microwave coverage.

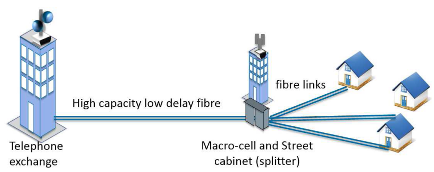

FIGURE 6. Last mile of the small cell backhaul is provisioned using fibre to the home (FTTH).

The study is thus based on published cost-related material mostly, and industry-based estimates where information is not readily available. The total cost of ownership (TCO) of each scenario is computed by adding the CapEX to the five years OpEX.

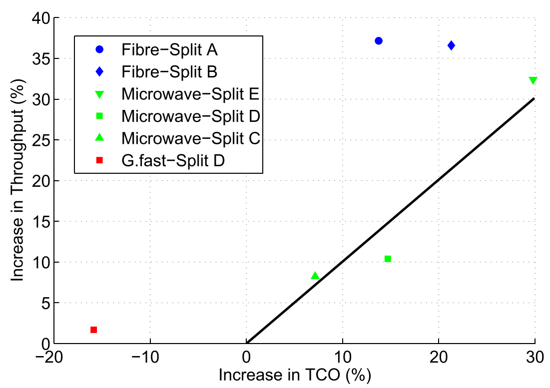

FIGURE 7. The increase/decrease in effective throughput of each scenario, relative to the benchmark scenario (D-RAN and G.fast), is compared to the corresponding increase/decrease in TCO. The diagonal line separates the profitable and non-profitable regions; scenarios that fall below the line indicate higher increase in TCO than in throughput.

Figure 7 displays the gains/losses of each of various deployment scenarios featuring variable levels of centralisation, compared to the D-RAN. The benchmark deployment scenario is D-RAN with G.fast; the capacity gains/losses of all other scenarios are derived by comparing their respective cumulative effective throughput to the benchmark.

In parallel, the increase/decrease in TCO of each scenario is also defined with respect to the same benchmark scenario. The diagonal line separates the region of advantageous from the unprofitable scenarios; those that fall on the line incur comparable cost increase and capacity gain, those below the line require higher cost than capacity gain achieved. The promising deployment scenarios are those that fall above the diagonal line since the capacity gains exceed the respective cost increase.

Scenarios deploying PtmP microwave are seen as the least interesting solutions since the resulting increase in capacity is comparable, if not less, than the incurred cost. The cost of PtmP microwave fronthaul may be reduced if more small cells fall within its coverage, however, that would increase the contention of cells to the shared bandwidth and may result in throughput degradation. The microwave solution considered here utilises a licenced spectrum; hence, different licence cost assumptions may alter the results and render the PtmP microwave solution more attractive. Interestingly, centralisation of MAC and FEC coding/decoding (Split D) results in considerable reduction in cost (16%), while maintaining comparable throughput as the benchmark scenario. This may be a efficient migration strategy from D-RAN to C-RAN that relies on existing backhaul infrastructure. Contrary to common belief, the case study shows that the C-RAN architecture with fibre-based fronthaul is profitable when considered from a joint backhaul/RAN perspective. The capacity gain is almost double the incurred increase in TCO owing to the RAN cost reductions due to centralisation and the throughput boost on account of the unlimited fronthaul capacity.

Although these results cannot be conclusive because they depend on delicate cost assumptions; nonetheless, some useful insights can be drawn. In the presented case study, the highest gain reached with centralisation is 37% increase in effective throughput; on the other hand, the highest increase in cost is 30%. Thus, the gain from centralisation dominates the increase in TCO, even when fibre to the cell is assumed. But perhaps a more critical factor than cost is the practicality of laying fibre, which is difficult to capture in the analysis.

IV. STATE-OF-THE-ART RESEARCH FOR 5G BACKHAUL

Recent years have witnessed a plethora of diverse efforts, from different research bodies, related to the future of backhauling, including network operators, equipment manufacturers, and academia. The topics of research cover a very broad area and are often interrelated. Hence, it is challenging to list all related research, in view of the profusion of publications, and even more to categorise them, because they often overlap. Nonetheless, we identify an essential and representative group of topics that could jointly pave the way to defining the 5G backhaul. Each of these research directions could be discussed in a dedicated survey with more technical depth; however, the scope of our survey is to explain the entire 5G backhaul problem and compile a representative list of key and state-of-the-art references. Recent advances in optical networks will first be covered, since fibre is often the preferred technical choice for backhaul (Section IV-A). Next, we introduce recent work on mmWave, among other wireless technologies; a promising alternative for the last mile, where fibre is not possible (technically or economically) (Section IV-B). This will be followed by a section detailing the arrival and integration of SDN in the transport network, covering both optical and mmWave technologies among other topics (Section IV-C). Energy efficiency in backhauling is another important subject that has gained serious attention, and touches on different technologies while often involving self-optimised networks (SON) capabilities (Section IV-D). Caching achieved great gains in the internet technology and is now being integrated into the mobile network at different levels, nonetheless affecting the backhaul (Section IV-E). Examples of joint RAN and backhaul design and optimisation will finally be presented to demonstrate the potential of this partnership in unlocking network bottlenecks (Section IV-F).

A. ADVANCES IN OPTICAL NETWORKS

Fibre optical connections are an ideal solution for connecting the fronthaul in view of their intrinsic low-latency-high-capacity characteristics, that match stringent requirements of the C-RAN architecture. Moreover, many cities in our days enjoy a reliable fibre network that could be further exploited to provide the mobile fronthaul. Ranaweenra et al. have explored the benefits of PtmP architecture, reusing existing laid fibre to the node, as opposed to PtP deployment in [62] and [63]. They show cost reductions reaching 60% with the usage of passive optical network (PON) with an aggregation node multiplexing/filtering 18 fronthaul connections to lamp-post small cells.

NTT DoCoMo provide a comparative analysis of time division multiplexing (TDM) and wavelength division multiplexing (WDM) for a PtmP architectures in [64]. Currently, TDM-PON systems, such as GPON and GE-PON are deployed as FTTH, offering rates in the order of one Gigabit per second and are being upgraded to XG-PON and 10G-EPON, thus, taking TDM-PON to the 10 Gbps class. Accordingly, TDM-PON is a cost effective solution that could meet the capacity demand of 5G fronthaul; however, the incurred latency, especially on the upstream, is not compliant with requirements. Moreover, TDM-PON is a rigid architecture that hinders easy and dynamic adaptability and scalability, thus, limits resource pooling. On the other hand, WDM-PON allows physical sharing of fibre medium by several optical network units (ONU) while providing a virtual PtP architecture with a PtP wavelength realisation. WDM-PON solves all the issues facing TDM-PON, i.e., enables scalable, dynamic, and adaptive resource allocation at low latency. Of course, these advantages translate directly to a potential reduction in fibre links and lower capital expenditure due to resource sharing and pooling. Nevertheless, WDM devices, such as transceivers and multiplexers/demultiplexers, are still very costly to deploy and maintain, hence, the advantage on reduced CapEX is not fully reaped at this stage. Due to the inherent cost of WDM-PONs, NTT explore further the TDM-PON limitations and provide a solution for reducing the latency, which is mainly due to the dynamic bandwidth allocation (DBA) algorithm. In [16], they present a novel DBA which uses radio access control information to allocate the bandwidth on the fronthaul instead of waiting for uplink data transmission to trigger a report-gate dialogue between the ONU and the optical network terminal (ONT), hence, reducing latency to better than 40 μsec.

In another work, a hybrid TWDM-PON solution is proposed, which introduces fronthaul aggregation points managed with WDM-PON, and the ONUs within each fronthaul aggregation node are managed with a TDM-PON architecture [65]. This proposal offers a balanced solution between the simplicity and reduced cost of TDM while gaining a level of dynamic flexibility and adaptability from the WDM architecture. The standardization of the next-generation passive optical network stage 2 (NG-PON2) has been recently confirmed and relies on TWDM-PON system to provide 40 Gbps bandwidth [66].

An optical technology research group, introduces an orthogonal frequency division multiplexing (OFDM) scheme for the downstream combined with a TDM scheme for the upstream [67]. The use of OFDMA is motivated by the capability to establish virtual PtP links in the frequency-domain, thus, serving a high density of cells (200 cells in the simulations provided with more than 100 Mbps per cell). OFDMA cannot be used for the upstream since transmissions are uncoordinated, instead, a judicious hybrid of DSP-enhanced digital radio-over-fibre and TDMA is used, resulting in reduced latency (<1 msec). The solution proposed uses off-the-shelf devices such as avalanche photodiodes, consequently provides the required flexibility, with high capacity and low latency at a moderate cost.

SODALES[5] promotes the introduction of an active remote node (ARN) between the central office (CO) and end user, hence, creating an *active* (not passive) optical network [68]. The ARN architecture exploits the existing PON where available and employs mmWave technology otherwise to deliver high bandwidth wireless final-drop. Moreover, the ARN could also act as a central CPRI switch interfacing BBU located in the CO to many RRHs, thus, enabling the VeNB/C-RAN concept. Connecting fixed users through fibre and mmWave and mobile users by feeding eNBs or RRHs from within the same node is indeed a novel approach that promises 5G essential features such as scalability, adaptability, and efficiency in resource usage. An example is given of two 10 Gbps incoming wavelengths feeding the ARN, originating from an arrayed-waveguide grating passive node away from the central office. The ingress capacity is distributed in the ARN to provide 10 Gbps to each of three small business enterprises and one eNB and 1 Gbps to 96 residential users, thus, maximising the usage of backhaul resources. Although adding active components in the backhaul is normally undesirable in view of carbon footprint and added complexity, ARNs could share power supply with existing/planned eNBs, or could use renewable energy for the required 1.5 kW.

Fibre-optic-based backhaul is a leading attractive 5G solution owing to its superior performance relative to other technologies. Advances in this topic such as latency reduction and efficient multiplexing and aggregation are promising, however, they all require extensions in fibre links to connect the proliferation of small cells. On the other hand, FTTH or FTTB (building) coverage is still limited worldwide and the task of laying new fibre links to improve it is daunting in view of the cumbersome trenching and related exorbitant cost, discouraging telecommunication regulators and network operators from pushing for such an endeavour. To this end, an alternative solution, that is easy and cost-effective to deploy, is crucial in order to bridge the existing fibre-based network and the pervasive small cells in an ultra-dense network; mmWave may be such a solution as examined in the next section.

B. ADVANCES IN mmWave

The anticipated overwhelming capacity and data rates are faced with a legacy spectrum that is overloaded. Advanced features such as UDN, xICIC, CoMP, massive MIMO, and carrier aggregation are all essential features to reach the target capacity, but spectrum remains a barrier that needs to be unlocked. A. Goldsmith challenged the common belief of spectrum shortage in a recent talk asking "Do we have a shortage of bandwidth or imagination?" [69]. Indeed, a large chunk in the $60 - 100$ GHz spectrum remains untapped and seems to be an inevitable option for 5G. This bandwidth is largely unused, globally, but propagation characteristics within the said range differ greatly; accordingly it is often partitioned into two bands with the following popular terminology: 60 GHz band (or V-band) and the E-band (>60 GHz).

A pioneering EU FP7 project, BuNGee,[6] promotes the adoption of mmWave to enable broadband radio access networks, using mmWave self-backhauling [4]. T. Rappaport and his team have carried intensive work on validating and advocating the usage of 60 GHz, through field measurements for both scenarios: wireless mobile access and wireless backhaul/fronthaul [70]–[74]. Their work has set up the base for further research in this field by providing tangible propagation measurements and link outage results as well as propagation modelling. By virtue of its inherent high absorption and limited coverage, mmWave communication is immune to other cell interference, consequently allows tight frequency reuse and maximisation of spectrum efficiency. Line of sight is a strict requirement for mmWave connectivity, however, in a backhaul/fronthaul application, it would be less challenging to ensure a reliable connection since the endpoints of the

[5]Software-Defined Access Using Low-energy Subsystems.

[6]BuNGee: Beyond Next Generation Mobile Broadband. A project part of the 7th Framework Programme funded European Research and Technological Development.

link are fixed, thus, enabling high gain antennae located diligently.

Authors in [75] present mmWave as the prominent solution for UDNs in 5G, used for boosting data rates to ~10 Gbps at lower delays (~1 ms). Moreover, mmWave-based self-backhauling and interference-aware routing are proposed to avoid cumbersome and costly wired fronthaul connections. A work by the Commonwealth Scientific and Industrial Research Organization (CSIRO) offers a novel two-tier small-cell backhaul architecture that employs aggregation nodes and integrates sub-6GHz PtmP and PtP E-band links [76]. Local small cells are connected to an aggregation node by sub-6GHz PtmP and low-cost medium capacity PtP E-band links. In the top tier of the architecture, various aggregation nodes are interconnected by PtP LOS high capacity E-band links. The proposed architecture pledges a flexible and scalable heterogeneous solution with easy upgrades and additions.

In-band backhauling is another direction gaining momentum in 5G research, which consists of reusing the radio access for wireless backhaul links. The advantages of in-band solution stem mostly from the reuse of hardware and spectrum, thus, maximising resource utilisation and reducing CapEX. Authors in [77] provide a solution framework for supporting an in-band PtmP mmWave backhaul complemented with tradeoff analysis of gains and incurred reduction in radio access capacity. The joint in-band backhaul scheduling and interference mitigation in 5G HetNet is addressed in [78] as an optimisation problem with promising user throughput gains, especially for dense networks. mmWave deployment in HetNets is also the topic of [79], and is used for radio access and/or backhaul in TDD mode. A novel frame structure is presented that allows multiplexing and is backward compatible with LTE, in view of time slot dimensioning. Simulation results show that an aggregate cell throughput of nearly 13 Gbps is possible with 10 small cells per macro sector whilst using mmWave for both radio and multi-hop backhaul. The joint European-Japanese research project, MiWEBA, has adopted mmWave as the main enabler for 5G network, employing the technology for radio access and backhaul/fronthaul, empowered with control/user plane splits, cognitive radio, and C-RAN [50]. A recent article [80] examines the challenges of incorporating massive MIMO and mmWave technologies in 5G networks to "provide vital means to resolve many technical challenges of the future 5G HetNet".

Wireless connections are prominent contenders to filling the shortage gaps of optical fibre links in the 5G backhaul network. In-band backhauling is attractive since it does not require additional investments or spectrum license, but may not satisfy the bandwidth needs in many scenarios. PtmP microwave, requires additional spectrum license but benefits from high spectrum efficiency since it is shared by multiple small cells; nevertheless, may lead to shortage in bandwidth when simultaneous traffic peaks occur, as seen in Section III-D. mmWave entails minimum license cost, if any, and has ample bandwidth but suffers from vulnerability to shadowing which becomes crippling in a street-to-roof or street-to-street scenario. Moreover, mmWave propagation is limited and sensitive to weather conditions; however, advances in massive MIMO may be able to address this shortcoming. In brief, wireless backhauling is a promising alternative to fibre links; each of the solutions in this portfolio has distinctive advantages and shortcomings, but they are all easier and potentially cheaper to deploy than fibre optic links.

C. SDN IN THE BACKHAUL

Projections indicate that the market of SDN and network function virtualisation (NFV) market will reach \$11 billion in 2018 with 68% share from new segments [81]. These are mostly the virtualised network functions (VNF), but also ports, routers, switches, and optical gear that have become SDN-capable. Open Networking Foundation (ONF) is the engine behind the promotion and adoption of SDN through open standards development (e.g., OpenFlow). SDN essentially decouples control from the data forwarding function, in a programmable manner, thus, creating "a dynamic, manageable, cost-effective, and adaptable architecture that gives administrators unprecedented automation, and control" [82].

SDN is certainly taking cellular networking by storm, and is seen as a crucial facilitator to 5G networks by many key players. SODALES's vision is that SDN will allow multi-operators, with multi-RAT technology, to share the same heterogeneous physical network, thus, exploiting resource utilisation and reducing CapEX and OpEX [83]. SDN-enabled fronthaul is proposed, by the same group, using CPRI over Ethernet and the ARN, as detailed in [68]. Furthermore, distributed security is implemented, using SDN, with direct links that are confined inside the access domain, hence, achieving low latency.

NEC's research group introduces, in [84], a novel software defined networking tool: the backhaul resource manager, to provision a flexible high-capacity hybrid mmWave/optical mobile backhaul network. In the proposed architecture, 60 GHz and E-band mmWave technologies are employed for high-capacity last mile and pre-aggregation backhaul, complemented with OFDMA-PON as previously introduced in [67]. The backhaul resource manager performs automated dynamic resource provisioning and capacity-aware path computation, consequently improving fairness, network utilization and end-to-end user QoE. The same group adopts OpenFlow to enable software-defined λ-flow architecture for flex-grid OFDMA mobile backhaul over PON in [85] and [86]. Furthermore, they propose an SDN-controlled optical topology for reconfigurable fronthaul for bidirectional CoMP and low latency inter-cell device-to-device (D2D) connectivity in [87].

Authors in [88] and [89] propose a virtualised architecture for next generation systems in which the control plane consists of a group of SDN applications starting from the base stations i.e., VeNB, backhaul transport, mobility management, radio access, caching, monitoring, and service delivery. The backhaul is realised through the usage of OpenFlow and carrier grade Ethernet switches, where the I-SID (Instance service ID in 802.1ah) is used to mark the path between the first aggregation point and the internet gateway, the B-VLAN (backhaul virtual local area network) tag to separate traffic of different virtual operators and the C-VLAN (customer VLAN) to identify a user in one eNB.

SK-Telecom endorse SDN in the transport network, and propose an SDN-based unified Converged Transport Network in [90]. They also report on successful SDN transport projects, such as Google, who used SDN to improve their resource utilisation, and CORONET who employed SDN to automatically and efficiently reconfigure the network and data distribution in case of natural disaster. A recent work in this context demonstrates the strength of SDN in optimising the performance of the mobile backhaul network by dynamically finding the optimum backhaul route (based on latency and available capacity), allocating required wavelength, and instantiating the location of the local controller (or BBU) [91]. The authors assume a fibre-based meshed network and show great improvement in throughput and reduction in packet loss with the proposed SDN-based algorithm.

The strengths of developing an SDN-based backhaul are manifold. Firstly, the inferred separation of control and data forwarding facilitates the co-existence of heterogeneous backhaul links. In addition, such an architecture expedites the possibilities of adding, extending, and dynamically reallocating resources in the backhaul network. On the other hand, SDN avails the backhaul network for multi-operators and multi-technology sharing, dampening the cost per bit to the end user and maximising the resource usage efficiency. Similar endeavours to engage competing network operators into sharing network infrastructure have often been faced by reluctant concerned parties. However, the fact that SDN allows network operators to have virtual control over their backhaul may succeed in convincing them, especially when affronted with the deterring cost of building, operating, and maintaining the 5G backhaul. On the other hand, the separation of control and data forwarding exposes the network to security challenges, especially when used with cloud computing, due to malicious usage or malfunctioning in the system. Authors in [92] expose security breaches that may result from masquerading as a data plane and overwhelming the control plane with denial of service (DoS) attacks, or errors in the system or malicious software that compromises the security of the control plane. Some solutions are proposed, nevertheless impacting on the system response latency and, in some cases, limiting the scalability of the network.

D. ENERGY EFFICIENCY IN THE BACKHAUL

Energy efficiency, in next cellular generations, is a global and paramount requirement driven by the desire to reduce communication carbon footprint, as well as energy bills, and extend terminal battery life. 5G systems are expected to cater for the explosive rise in devices and capacity without causing a dramatic increase of energy consumption. Until recently, studies on energy consumption of wireless communication systems have diverted from the backhaul contribution, due to its trivial role in macro-cell networks (5% according to [93]). However, with the invasion of small cells, blossoming of HetNets, and creation of UDNs, the backhaul mark of energy consumption is expected to grow to 50% [93]. Consequently, solving the backhaul bottleneck entails looking at the energy aspect which is as important as capacity and latency.

Tombaz et al. consider three deployment scenarios for the future backhaul: fibre to the node (FTTN) with VDSL2 to the cell, microwave, and a hybrid solution of fibre to the building (FTTB) and microwave [93]. Through simulations, they show that the first deployment scenario is more energy efficient than the one that employs microwave only, whereas the hybrid scenario outperforms both in a UDN, capitalising on existing fibre infrastructure. In another work, mmWave for backhaul is investigated from an energy consumption point of view comparing different spectrum bands and deployment scenarios [94]. As expected, provisioning wireless backhaul frequencies at lower frequencies results in higher energy efficiency. Moreover, in a small cells network, the energy consumption difference resulting from the wireless frequency becomes negligible in view of the high gain realised with the backhaul architecture.

An earlier EU FP7 project, BuNGee, proposes a joint design of backhaul and access networks, using heterogeneous radio elements and a cognitive radio backhaul approach enabled by SON capabilities [4]. In one of their publications they offer a green-oriented implementation of the cognitive backhaul [95] in which user association is geared towards prioritising RRHs with higher load, when possible, to allow a higher number of RRHs to be in sleep mode, thus, economising energy.

Motivated to design green networks, authors in [96] and [97], propose an ICIC resource allocation scheme that is energy-aware, thus, improving energy efficiency (by up to 50%) at the expense of reduction in spectrum efficiency. Backhaul energy consumption is incorporated in the total energy budget, and fibre is shown to consume less energy than microwave in a heterogeneous backhaul. Authors in [98] first study the energy impact of various backhaul technologies under two scenarios: uniform UE distribution and hotspot. They show that mmWave is the most efficient solution and that the backhaul could consume up to 78% of total energy if provisioned using sub-6GHz technology in a hotspot scenario. Next, they elaborate an energy-aware cell-association scheme based on cognitive heuristic algorithm with two objectives. It first exploits the available context-aware information to find the path with the least number of hops, in order to minimize the backhaul energy consumption. Then it selects the less loaded backhaul route, in case more than one option is available, to achieve load balancing. The proposed algorithm is shown to consistently improve energy efficiency, especially in a hotspot scenario, in which 42%

amelioration is seen compared to the normal UE association criteria being the reference signal received power (RSRP).

Green 5G network operation is no more optional and the rapidly rising role of the backhaul in energy consumption makes energy efficiency an imperative 5G backhaul objective. The major challenge, however, is to achieve this goal without compromising other performance indicators such as user throughput or network mean packet delay. This recent dimension renders the 5G network (both RAN and backhaul) optimisation highly complex with multi-objectives and multi-constraints. To this end, SON becomes an essential tool in this endeavour. 5G network elements such as radio cells, aggregation points, routers, etc., need to be equipped with SON while the holistic optimisation is orchestrated jointly by the RANaaS and a similar backhaul entity.

E. CACHING FOR THE BACKHAUL

A promising way, that is rapidly gathering momentum, for solving the backhaul bottleneck, is to cache the content at the edge of network, namely at the small cells and UEs. Caching, thus, transforms the network intelligence from being ''reactive'' to ''proactive'', and leverages the latest developments in storage, context-awareness, and social networking [99]. Thus, if user data was predicted and cached in advance during low traffic periods, it can be transmitted during peak hours without burdening the backhaul while still achieving good QoE.

Bastug et al., in [100] elaborate on the role of caching in a small cell network, with respect to backhaul alleviation and D2D communication, when the context is pre-stored in a UE within reach. Authors in [101] propose a distributed algorithm, based on alternating direction method of multipliers, to optimise the choice of files from a fixed catalogue for every storage-capable small cell. Another paper proposes a user association scheme that aims at improving user QoE by exploiting small cell caching capabilities to overcome backhaul constraints [102]. In the proposed approach, small cells individually look at content availability, realisable data rates (with respect to interference and backhaul capacity) and decide which UEs to serve accordingly.

A novel solution framework of cache-induced opportunistic CoMP, enabled by caching a portion of media files at the small cells, is proposed in [103]. The challenge is to decide on which files to pre-code, how to generate constructive MIMO pre-coding, and in which small cells to store the pre-coded file. The mixed-timescale (short term for MIMO pre-coding and long term for cache control) optimisation problem is solved by exploiting the timescale separations.

A novel cache-aware user association algorithm is proposed in [104] which minimises the backhaul usage of each small cell while respecting the quality of service (QoS) requirements of users. A survey on recent progress in this field is provided in [99] with a historic on usage of caching, benefits, and integration in cellular networks.

Nonetheless, the success of caching remains conditional upon many challenges ahead, such as the storage capacity of cells, very large catalogue size of users' files, and the need for fast and dynamic learning of cells while making the caching decision. These challenges have been exposed in [105], in which the authors exploit big data and apply machine learning for the purpose of proactive caching. Although major complications remain unsolved, the potential of caching is nevertheless promising, rendering it a prominent 5G backhaul research direction.

F. RAN/BACKHAUL JOINT DESIGN AND OPTIMISATION

Although 3GPP considers that the backhaul is a separate entity from the RAN, nonetheless, most research paths discussed so far require some level of coordination between the backhaul network and the radio access network. Indeed, advances in optical technologies are geared towards dynamic wavelength allocation, coordinated RAN and backhaul resource allocation, and the addition of the active remote node, which all benefit from having access to RAN information (see Section IV-A). A major part of research, related to mmWave, considers in-band backhauling or rely on cognitive radio, equipped with intelligence solicited from RAN, thus, joint RAN and backhaul operation is crucial (see Section IV-B). Energy efficiency in backhauling tackles wired and wireless backhaul access technologies and architectures as part of the global energy consumption model, thus, requires close collaboration between RAN and backhaul to yield constructive results (see Section IV-D). Research on SDN-enabled transport network intersects with all other listed study groups and acts as an enabler to dynamic, flexible, and adaptive green backhauling. Accordingly, SDN benefits and builds on coordination and information exchange between RAN and backhaul (see Section IV-C). Caching is another feature that capitalises on context-awareness and instantaneous network information (e.g., system interference, QoS requirements, and backhaul capacity) to achieve gains in alleviating the backhaul traffic during peak hours, consequently, coordination between RAN and backhaul is essential (see Section IV-E).

An aggressive joint radio access and backhaul design was introduced by the BuNGee project earlier in 2010-2012, promoting the benefits of such joint operation for the purpose of optimised performance and efficiency [106]. The outcomes of the BuNGee project were used in the ETSI (European Telecommunications Standards Institute) technical reports on Broadband Radio Access Networks (BRAN [107], [108]). iJOIN's view of network evolution towards 5G is that ''...blurring borders between access and the backhaul networks require a joint design of both...'' [6]. iJOIN have identified joint backhaul/RAN design as a prime enabler to next generation networks and have pinned the terminology RAN as a service RANaaS to define a flexible RAN architecture that is neither fully distributed nor fully centralised [6]. Furthermore, the backhaul and RAN cooperation is classified in two distinct categories: backhaul/RAN awareness and joint RAN/backhaul functional design [109].

Examples of backhaul/RAN awareness are many, such as backhaul aware resource allocation (e.g., [96], [97]) and cell association (e.g., [110]). A recent work looks at adjusting the radio coverage of a cell in view of backhaul availability and capacity, exploiting reinforcement learning to adjust the cell range extension offset [111]. The RAN uses backhaul information to redistribute users in a way that maximises user QoE and that adapts to temporal backhaul constraints. Thus, the proposed scheme is a typical joint backhaul/RAN awareness, realised using SON capabilities. Authors in [112] use a centralised optimisation mechanism to also adjust the cell range extension offset, in order to minimise the mean network packet delay. Another new article addresses the issues of backhaul latency and resilience through a backhaul-aware user association that aims at improving QoS while balancing the network load [113]. A recent paper by N. Wang et al. offers a radio resource management perspective to the 5G backhaul problem [114]. The authors discuss the potentials of backhaul-aware resource allocation in a multi-RAT environment and propose the usage of a unified wireless backhaul bandwidth allocation in a small cell case study employing in-band backhauling and massive MIMO.

On the other hand, joint functional design consists of network-wide functionality such as global energy efficiency optimisation (e.g., [93], [95]) or spectral efficiency maximisation (e.g., [77], [79], [115]). iJOIN in [9] present a novel architecture for next generation systems in which data and control planes are decoupled. RRHs are used for data offloading, but an anchor point (that ideally overlooks several RRHs) is dynamically configured for the control plane. A network controller node, that communicates with the VeNB controller and the SDN-enabled backhaul, finds an adequate anchor point for each incoming UE, based on QoS. It also determines the backhaul optimal route based on the anchor point, QoS, as well as the current network status, taking into account energy consumption in the RAN and backhaul, congestion, and requirements of the VeNB.

Another advantage of joint design reported in [6] is the flexible control of CoMP modes depending on application requirements, network status, and backhaul constraints. Another perspective is offered in [115] which proposes in-band TDD backhauling and optimised resource allocation scheme that maximises user throughput. A recent work by Wang et al., illustrates the potential of SDN-based framework for joint RAN and backhaul operation through logically centralized management of IP-based mobility and energy consumption [116].

5G network operators are concerned with one prime objective: maximise their revenue. To this end they need to maximise the users' QoE to increase their market share while minimising the network expenditure. In previous networks, the radio access was the main bottleneck and the network optimisation consisted largely of reducing the number of cells and maximising their spectral efficiency. On the other hand, 5G comes with broader challenges and new opportunities, as detailed in Section II, and network optimisation has become an end-to-end endeavour in which joint RAN/backhaul design plays a central role.

V. CONCLUSIONS AND OUTLOOK

5G backhaul research is probably at its peak and is witnessing a profusion of published papers and focused research from key 5G players. Unlike incumbent cellular generations, 5G is partly an evolution of existing technologies but is also based on disruptive technologies affecting all parts of the network, nonetheless the backhaul, and revolutionising the traditional approaches to network design. As a result, the 5G backhaul challenges are manifold: $>$10 Gbps capacity, $<$1 msec end-to-end latency, high security and resilience, time and frequency synchronisation, low energy consumption and low cost. None of the current backhaul solutions can deliver all of the above as a stand-alone solution; perhaps fibre-optic-based backhauls rank the best in all aspects, except cost. To this end, the backhaul portfolio has broadened to include new technologies, such as mmWave and sub-6GHz spectrum, in-band backhauling, in addition to innovations in wired backhaul technologies. Besides, heterogeneity prevails in 5G networks and describes all network elements including users, services, RAN, and backhaul. Consequently, a realistic 5G backhaul is one that is comprised of many backhaul technologies. Besides, it is flexible, adaptive, dynamic to allow catering for the 5G stringent performance needs where possible (and needed) whilst adapting the RAN network to its hard limitations and constraints in case of more relaxed requirements.

The survey identifies six key research directions that would jointly pave the way to 5G backhaul, as presented in Section IV. Key surveyed sources are tabulated in Table 8, highlighting, in each case, the sub-topics covered such as backhaul technologies, optimisation objective, RAN architecture, and RAN options, among others.

A. LESSONS LEARNT

Key lessons drawn from the inspection of the 5G backhaul problem and state-of-the-art related literature are summarised below:

- Lesson 1: In summary, there is no-one-solution-fits-all in 5G backhaul and, more importantly, there is no unique set of 5G backhaul requirements. The main lesson learnt, towards designing the future backhaul, is that we need to make the best of existing transports networks, evolve incumbents solution (e.g., xPON), and explore new technologies such as mmWave, sub-6GHz, FSO, etc.
- Lesson 2: Dynamic, adaptive and flexible operation of the 5G backhaul is the most stringent requirement, stemming from the heterogeneity of the backhaul and network requirements and the need to efficiently adapt network resources in a timely manner.
- Lessons 3: Moreover, the fusion of the RAN and backhaul is a dominant shift, rendering the joint design, operation, and optimisation of both traditional parts of the network crucial to the success of 5G. Thus, a

TABLE 8. State-of-the-art categorised research and sources.

Direction	Fibre optics	mmWave	Other BH technologies	SDN	Energy efficiency	Caching	Joint RAN/Backhaul	Backhaul throughput	Backhaul latency	Backhaul synchronisation	C-RAN	C-plane/U-plane Split	UL/DL decoupling	Cost	SON
[4]		✓			✓		✓				✓	✓			✓
[6]	✓	✓	✓		✓		✓	✓	✓		✓				
[8]	✓	✓	✓						✓	✓	✓				
[9]							✓	✓	✓		✓				
[10]	✓		✓		✓			✓	✓			✓			
[12]–[14]	✓							✓	✓	✓	✓				
[16]	✓						✓	✓	✓		✓				
[17]	✓	✓	✓				✓	✓	✓		✓				
[18]–[20]	✓		✓					✓	✓	✓					
[21]	✓	✓	✓		✓		✓	✓	✓	✓	✓				
[24]	✓	✓	✓					✓	✓	✓					
[31]	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓				
[33], [34]		✓						✓	✓						
[35]								✓							
[43]								✓			✓				
[45]	✓	✓	✓					✓	✓	✓	✓				
[46]	✓	✓	✓					✓	✓	✓	✓				✓
[49]							✓	✓					✓		
[50]	✓	✓	✓		✓			✓	✓		✓	✓			
[51], [52], [55]	✓		✓											✓	
[53]	✓														
[56]			✓					✓	✓						
[57]		✓	✓							✓	✓				
[58]	✓		✓					✓	✓						
[59]								✓	✓		✓				
[60]	✓	✓	✓					✓	✓		✓				
[61]	✓		✓				✓	✓			✓			✓	✓
[62], [63]	✓							✓						✓	
[64], [65]	✓						✓	✓	✓		✓	✓			
[67]	✓							✓	✓						
[68]	✓	✓	✓					✓	✓		✓				
[71]–[75]		✓													
[76]		✓						✓							
[77]	✓	✓	✓					✓	✓						
[78], [79], [81]	✓							✓	✓						
[80]	✓	✓						✓	✓						
[84]	✓	✓	✓	✓				✓	✓	✓	✓				
[85]		✓		✓				✓	✓						
[86]–[88]	✓			✓				✓	✓						
[89]–[91], [93]				✓											
[92]	✓			✓				✓	✓		✓				
[94]	✓		✓		✓										
[95]	✓	✓			✓										
[70], [96], [107]	✓	✓		✓	✓			✓	✓						✓
[97], [98]	✓		✓		✓			✓	✓						
[99]	✓	✓	✓		✓			✓	✓						
[100], [101], [104]						✓		✓	✓						
[102]						✓		✓	✓						✓
[103] [105]						✓	✓	✓	✓						
[110]	✓	✓	✓		✓		✓	✓	✓	✓	✓				
[113], [115]	✓	✓	✓				✓		✓						
[114]	✓						✓	✓	✓	✓					
[116]		✓					✓	✓							
[117]	✓	✓	✓	✓	✓										
[118]	✓						✓							✓	
[119]							✓	✓						✓	
[107]–[109]		✓			✓		✓	✓	✓		✓	✓		✓	✓
[112]	✓	✓					✓	✓	✓						✓
[120], [121] [122], [123]	✓ ✓	 ✓	✓ ✓						 ✓					✓ 	

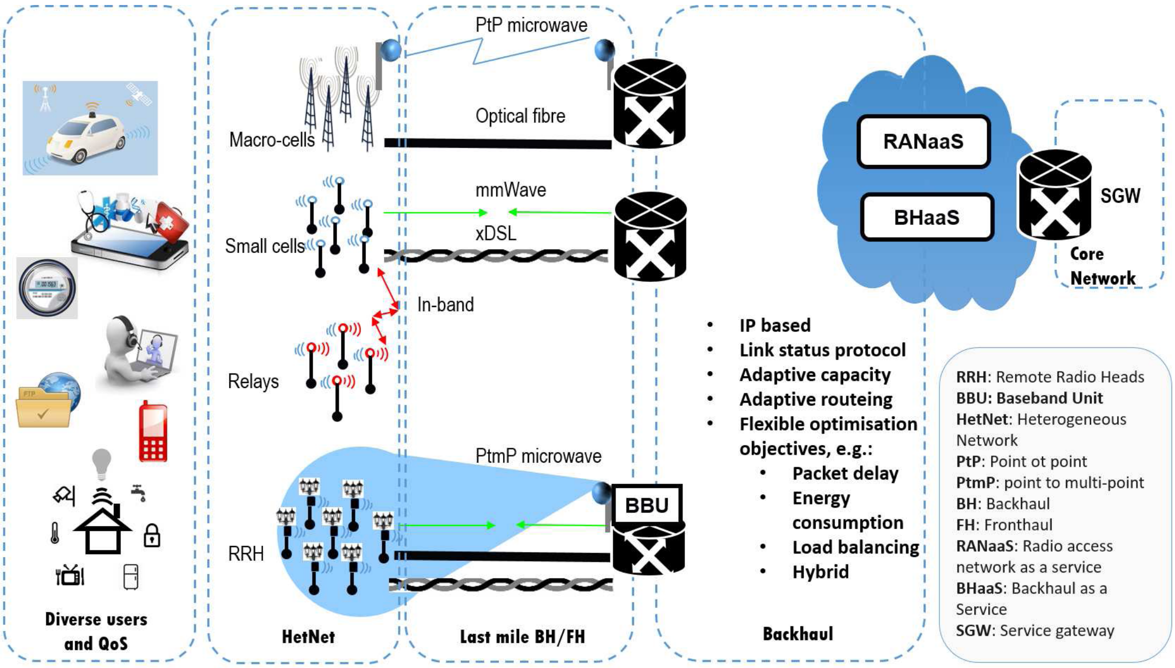

FIGURE 8. **Heterogeneous radio access and backhaul networks with diverse user devices and applications. The joint BHaaS/RANaaS collaboration allows network-wide visibility and enables dynamic optimised network operation. The BHaaS overlooks the backhaul network operation and adapts it based on information from the RANaaS such as adjusting routeing tables, optimising bandwidth allocation for egress/ingress traffic flows, traffic balancing, self-healing, etc.**

joint RAN/backhaul perspective is critical in assessing backhauling solutions, leading to different outcomes when compared to the RAN-unaware backhaul ranking. We have shown that some levels of RAN centralisation are always beneficial, even when deployed with copper-based backhaul and that the gain attained from C-RAN with fibre-based fronthaul prevails the incurred cost, rendering the solution more advantageous than previously believed.

- Lesson 4: The overwhelming growing size of the network and relevant parameters, and the mesh-like growth of the 5G backhaul dictate employing SON to automate organisation and optimisation of the network in a distributed manner. The main advantage of SON is its fast adaptability to the dynamic network, relative to a centrally optimised solution. The challenge is to design efficient SON algorithms with low complexity to avoid an increase in cost and energy consumption of network elements that employ these algorithms.
- Lesson 5: Another critical lesson, drawn from this research, is that technology adoption from information technology (IT), such as SDN, will play a key role in the 5G backhaul evolution. These technologies are facilitators to backhaul management in the presence of heterogeneity but also render infrastructure sharing more attractive to various concerned parties, leading to reduced cost and energy consumption. However, an SDN architecture may expose network security; an open problem that should be addressed without compromising the network adaptability and flexibility.

B. CONSOLIDATED 5G BACKHAUL SOLUTION

Based on the lessons learned, a promising 5G backhaul vision would be part of a whole network restructuring in which there are no boundaries between radio access and transport network. Indeed, the RAN functionality would be presented as a cloud-service, RANaaS, and joint design and optimisation of RAN and backhaul as a solution to coordinated evolution (refer to [6]). Interworking of access and backhaul networks would enable dynamic functional split in the C-RAN in view of constraints and requirements from both domains, and dynamic link setup in the heterogeneous backhaul network based on UDN status.

A new SDN-enabled *network layer function* that has global network visibility, would complement the joint RAN/backhaul architecture, thus, allowing fully coordinated RAN and backhaul operation. Such a solution would provide the crucial flexibility, scalability and adaptability needed, and would allow opening the physical network to multi-operators with multi-RAT and multi-vendors while enforcing required security and virtual individuality (mobile virtual network operator MVNO). This forms the utmost level of resource sharing and pooling, hence, meets cost constraints in both capital and operational expenditures. Indeed, the 5G PPP present their 5G vision as one that“... will integrate networking, computing and storage resources into one programmable and unified infrastructure” [121]. They foresee that telecom and IT will be integrated towards a common, very high capacity, ubiquitous infrastructure in 2025. Hence, the evolution and integration of SDN/NFV is seen to play an essential role.

Based on this survey and key players' visions of 5G, the consolidated 5G backhaul solution can be provisioned as a service (BHaaS), that is part of a software defined network, with common RAN intelligence, SON, and caching capabilities, that operates on a heterogeneous physical network of wired and wireless connections as shown in Figure 8. The joint BHaaS/RANaaS collaboration ensures a holistic visibility to the end-to-end network and enables coordinated optimisation and operation. The BHaaS, based on gathered backhaul and RAN dynamic network data, performs the first level of optimisation which entails adjusting the prioritisation of network goals and disseminating network faults, additions, load, etc. The second level of optimisation is SON-based and distributed over the network elements (e.g., routers, gateways, aggregation points, multiplexers, radio cells, etc.), but is guided by the information stemming from the BHaaS. Consequently, the backhaul network is inherently RAN-aware and dynamically adapts to network changes and conditions.

In order to demonstrate further of the BHaaS, as presented in Figure 8, we present typical examples of information flow. As proposed in [109], the RANaaS dynamically controls the "flexible" Cloud-RAN based on backhaul changing capabilities and constraints; the BHaaS, in this case, has the complete visibility of the backhaul network conditions and is able to report required information to the RANaaS, allowing backhaul-aware RAN service provisioning. Backhaul network status information is permanently changing due to varying traffic load, link outages, router faults or overloading, etc. In this case, the role of the BHaaS becomes even more important when multiple operators including cellular and fixed service provisioning share the same backhaul network. In such situations the RANaaS would not have access to full backhaul information whereas the BHaaS, owing to its network virtualisation capabilities would be able to liaise the needed information without breaching operators confidentiality. On the other hand, the BHaaS collects timely information related to the RAN status from the RANaaS and dynamically adjusts the routeing tables, ingress/egress bandwidth, and link optimisation based on various needs and traffic conditions from the RAN. Another example pertains to the backhaul-aware user-cell association, such as presented in [111], in which the radio access cells need to be continuously informed of the link status information of the connecting fronthaul/backhaul to adjust the virtual cell ranges accordingly. In such a scenario, the BHaaS manages the exchange of this information, which could include capacity, delay, energy efficiency, resilience etc.

C. UNSOLVED CHALLENGES

Progress from the research community is reducing the gap between 5G backhaul requirements and backhaul capabilities, however, major challenges remain along the way. The dominant disparities are capacity, synchronisation, and latency. We have demonstrated in this survey that advances in technologies such as fibre, copper, mmWave, sub-6GHz, and FSO have scaled down the capacity challenge considerably. However, these solutions are not fully developed yet and suffer from high cost, unreliability, or shortage of bandwidth. The remaining challenge is developing and intelligent,

TABLE 9. Abbreviations.

10G-EPON	10 Gigabit EPON
ARN	Active Remote Node
BBU	Baseband Unit
BHaaS	Backhaul as a Service
CapEX	Capital EXpenditure
CB	Coordinated Beamforming
CO	Central Office
CoMP	Coordinated Multi-point Processing
CPRI	Common Public Radio Interface
C-RAN	Cloud/centralised RAN
CS	Coordinated scheduling
CSI	Channel State Information
D2D	Device to Device
DAS	Distributed Antenna System
DBA	Dynamic Bandwidth Allocation
DL	Downlink
DOCSIS	Data Over Cable Service Interface Specification
eICIC	enhanced ICIC
EPON	Ethernet PON
FDD	Frequency Division Duplex
FEC	Forward Error Correction
feICIC	further enhanced ICIC
FFT	Fast Fourier Transform
FSO	Free Space Optical communication
FTTx	Fibre To The Node/Building
G.FAST	Fast Access to Subscriber Terminal; the letter G stands for ITU-T G series of recommendations
GNSS	Global Navigation Satellite System
GPON	Gigabit capable PON
HARQ	Hybrid Automatic Repeat Request
HetNet(s)	Heterogeneous Network(s)
ICIC	Inter-Cell Interference Coordination
IFFT	Inverse Fast Fourier Transform
ISP	Internet Service Provider
IT	Information Technology
JR	Joint Reception
JT	Joint Transmission
LOS	Line Of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
mmWave	Millimetre wave
MUD	Multi-User Detection
NFV	Network Function Visualisation
NGPON	Next Generation PON
NLOS	Non LOS
OFDM	orthogonal frequency division multiplexing
ONT	Optical Network Terminal
ONU	Optical Network Unit
OpEX	Operational EXpenditure
PON	Passive Optical Network
PtmP	Point to multi-Point
PtP	Point to Point
QAM	Quadrature amplitude modulation
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RANaaS	RAN as a Service
RAT	Radio Access Technology
RF	Radio Frequency
RRH	Remote Radio (RF) Head
RRU	Remote Radio Unit
SDN	Software Defined Network
SON	Self Organising/Optimising Network
TCO	Total Cost of Ownership
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TVWS	TeleVision White Space
UDN	Ultra Dense Network
UE	User Equipment
UL	Uplink
VDSL	Very high bit rate Digital Subscriber Line
VeNB	Virtual enhanced Node B
WDM	Wavelength Division Multiplexing
XGPON	10 Gigabit capable POND

adaptive, and dynamic adoption and allocation scheme of these solutions in an optimised manner that capitalises on the heterogeneity of the backhaul network while catering for the diversity of users' requirements.

There are two types of synchronisation: frequency and time/phase. Frequency synchronisation is needed in all cell deployment use-cases but is also possible with most backhaul solutions such as xDSL, xPON, and PtP connections. Phase and time synchronisation is required with features such as CoMP but is not available in all backhaul techniques. Global navigation satellite system (GNSS) assistance is a possible solution in some cases, but increases the complexity and cost of the small cells and does not operate in indoor small cell solutions. Arguably, indoor small cells are unlikely to employ CoMP schemes, nevertheless, the need and incurred cost of GNSS on all outdoor small cells motivate more research towards alternative solutions for phase and time synchronisation.

However, the prevailing difficulty resides in bringing the backhaul latency to the required levels of C-RAN and CoMP, i.e. down to 150 μsec (see Table 4). Currently, direct fibre and mmWave are the only technologies capable of such low delay, but future research is expected to make more options available. However, direct fibre is often not available and would be too cumbersome to lay, and mmWave is, relatively, a low-cost emerging technique facing major challenges related to propagation. This limitation has many implications and is predicted to be a leading research motivation.

Another key challenge is to capture the diverse performance aspects of the 5G heterogeneous transport network in an analytical model, to enable evaluation and assessment of innovative 5G backhaul solutions. Different works have addressed modelling of various backhaul performance indicators. For instance, the cost of the backhaul network has been modelled in view of the technology deployed and the network topology in different works, such as [117]–[119]. Authors in [120] and [121] propose analytical models to capture the delay of the backhaul network assuming it is wireless or heterogeneous (i.e., a combination of wired and wireless technologies), respectively. Authors in [120] model the delay in networks using heterogeneous backhaul solutions, composed of fibre links, xDSL, mmWave, and sub-6 GHz, and derive the mean packet delay over both the radio and backhaul networks. Given that energy consumption has pivotal importance in future networks, recent works have addressed modelling this aspect based on carried traffic and topology, such as [122] and [123]. Reliability and security of the backhaul are also critical and are captured in the proposed analytical model in [124]. This is certainly a key research direction that still requires development to represent fully the performance and constraints of a heterogeneous 5G backhaul network composed of different backhaul technologies.

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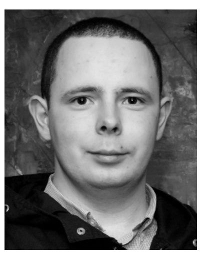

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